ASSESSING THE POTENTIAL OF AUTONOMOUS TRANSIT SHUTTLES AS A FIRST-AND-LAST MILE PUBLIC TRANSPORTATION SOLUTION

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For Grace, whose daily commute inspired this research

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LIST OF SYMBOLS AND ABBREVIATIONS

ABM	Activity Based Model
ARC	Atlanta Regional Commission
AV	Automated vehicle
DOE	US Department of Energy
FTA	Federal Transit Administration
GPS	Global positioning system
GREET	Greenhouse gases, Regulatory Emissions, Energy, and Transportation Model
GTFS	General Transit Feed Specifications
MARTA	Metropolitan Atlanta Rapid Transit Authority
MOD	Mobility-on-demand
MOVES	MOtor Vehicle Emission Simulator
OD	Origin-destination (from an origin to a destination)
PTW	Pump-to-wheels
TCQSM	Transit Capacity and Quality of Service Manual
TOD	Transit-oriented development
WTP	Well-to-pump

SUMMARY

Automated vehicle (AV) technology has the potential to improve safety and vehicle energy efficiency, increase mobility, lower travel costs, and increase roadway capacity. Much of this potential, however, relies on how the vehicles are deployed and the resulting shifts in travel behaviors. If the travel cost and mobility improvements are realized, the success of AVs could come at the expense of public transit ridership. Facing this modal competition, there may be an opportunity for transit agencies to integrate AVs into their existing systems as a first-and-last mile solution for riders; merging the efficiencies of passenger rail and mass transit with the door-to-door convenience of personal vehicles.

This research assesses such a scenario to model whether there would be travel time, cost savings, and other impacts to riders. Specifically, this research assesses the potential for on-demand, fully electric AV shuttles to serve as a first-and-last mile solution within 2.0-miles of all MARTA rail stations. A multi-modal routing platform was used to simulate trips and compare travel times between the proposed AV shuttle-transit service and the existing modal options of driving a conventional vehicle, walking to and from MARTA's current bus and rail network, and using park-and-ride lots to access MARTA. The routing platform used for this research also includes an energy module and a cost module, allowing the modal options to be compared on energy consumption per trip, and cost to the traveler. Demographic information tied to the trip data was retained, offering a high-level picture of potential populations served.

Nearly 7,000 trips were processed through the routing platform. On average, travel times for the simulated AV shuttle service were not competitive with conventional driving

(when parking time is excluded), but they were competitive with park-and-ride, and showed significant travel time improvements over MARTA's existing service. Driving also came in with the lowest average trip cost, excluding parking and sunk vehicle costs. In terms of energy consumption, the proposed AV shuttle service showed significantly lower energy use than the other modes. The AV shuttle service would offer other benefits as well, including expanding MARTA's effective service area, travel time savings for transit captive riders, and improved transit service for minority populations.

CHAPTER 1. INTRODUCTION

Automated vehicle (AV) technology, often referred to as autonomous vehicle technology, is rapidly advancing and is expected to be available to consumers within a decade (Belvedere (*1*)). AVs hold the promise of improving safety and mobility, increasing fuel efficiency, lowering emissions, reducing travel costs, and increasing throughput on existing roadways (Fagnant and Kockelman (*2*)). However, the future impacts of AVs on congestion and travel patterns remain unclear (Mokhtarian (*3*)). Similarly, the future impacts of AVs on public transit demand are also unclear. Some transportation industry stakeholders have speculated that AVs may render current public transit systems obsolete; replaced by smartphone apps and low-cost fleets of on-demand AVs moving travelers along the fastest routes to their destinations (e.g., Sperling (*4*)*;* Badger (*5*)). Others have suggested that transit agencies employ AVs as part of their service plans to bolster return on existing transit investments (e.g., (*4*); Korosec (*6*)).

This research examines the possibility of integrating on-demand AVs with existing transit service by assessing a scenario in which fully electric on-demand AV shuttles serve as an integrated first-mile and last-mile solution, or in this case a two-mile solution, for the Metropolitan Atlanta Rapid Transit Authority (MARTA). This research assesses a small fleet of AV shuttles based at each rail station and geofenced to serve up to a 2.0-mile radius, providing MARTA riders with on-demand and door-to-door connections to-and-from rail stations.

The primary study objectives are to assess differences in commute travel time, energy use, and cost between the proposed new AV shuttle service and three existing commute options of driving, taking MARTA bus and rail transit with walk access to the transit network, and taking MARTA transit after using park and ride access at rail stations. The findings are then used to assess time, productivity, or other costs and benefits for the riders across the demographic of the populations served.

This employs trip data, represented by origin and destination (OD) pairs, provided by the Atlanta Regional Commission's 2011 Travel Diary Survey (Livingston (*7*)). More than 12,500 trips (13.3 percent) of all 94,436. trips collected in the 2011 travel survey both began and ended within 2.0 miles of a MARTA rail station. These trips were processed through a multimodal passenger vehicle and transit routing platform developed by Georgia Tech researchers called Commute Alternatives (Li et al. (*8*)). Within the platform, RoadwaySim and TransitSim modules route each trip through the 202,000-link transportation roadway network and transit network from any origin to any destination. The simulators employ k-shortest path routines to identify the most efficient routes and route alternatives, minimizing travel time in this case, for multiple travel modes (drive direct, depart earlier, depart later, take transit with walk access, take transit with drive access, etc.). For each mode, the simulator retains the information on specific roadway links traversed, distance traveled, average speed per link, and calculates fuel use and emissions per link using the MOVES-Matrix model (Xu et al. (*9*); Xu et al. (*10*)). Energy consumption rates for the electric AV shuttles were generated separately using Autonomie, an advanced vehicle energy modeling software developed by Argonne National Labs and the US Department of Energy. The shuttle's energy use rates (which involve not only the on-road electricity use to move the vehicle, but the upstream electric power to produce and deliver the electricity) were then substituted into the routing platform in place of conventional vehicle energy use rates. Outputs for travel time, energy, and cost were then analyzed to assess potential impacts or benefits for riders.

Chapter 2 of this thesis provides background information and a literature review of AV shuttles, on-demand AV service, and idea behind pairing AVs with transit. Chapter 3 outlines the research scenario and parameters. Chapter 4 moves into the data sources and the routing methodology for each commute option simulated. Chapter 5 analyzes the travel time results, while Chapter 6 explores the differences in simulated travel times for different demographic groups. Chapters 7 and 8 examine the differences in energy use and cost across the three modes. Finally, Chapter 9 summarizes the study's conclusions, limitations, and provides recommendations for future work.

CHAPTER 2. BACKGROUND AND LITERATURE REVIEW

Much of existing literature contends that automated vehicles (AVs) are likely to increase urban sprawl, vehicle miles of travel (VMT), and total vehicle emissions; travelers may be willing to tolerate longer travel distances and times once they are free to sleep, work, or otherwise entertain themselves while the vehicle does the driving (*2*).

Transitioning to a fully automated fleet, however, will take decades. As long as AVs share the road with human drivers, the full potential of AVs to alleviate congestion and improve mobility will go largely unmet. During that transition, states, cities, and municipalities will need to address the potentially disruptive planning impacts of AVs, including how to contain sprawl, and how to maintain dense urban areas as desirable places for people to live, work, and play. Public transportation agencies will also need to account for the presence of both privately-owned AVs, and AV mobility-on-demand (MOD) AV services in their business plans. Transit agencies that do not adapt may face a slow but steady loss of ridership to increasingly more convenient and cost-effective transportation options. Emerging on-demand transportation options represent a potentially significant competitive risk for public transit systems. However, on-demand services may also offer a solution to current transit efficiency issues if existing public transit fleets can figure out how to work with emerging service providers to integrate shared shuttles into transit fleet services.

Numerous field-tested AV shuttles are already on the market. The Navya *Autonom*®, EasyMile *EZ10*®, and Local Motors *Olli*® are a few such examples. These electric shuttles carry 8-15 people and can operate at speeds around 25 mph. The Navya shuttles can run for 12-13 hours and fully recharge in 4-5 hours (Navya (*11*)). Pilot programs with these types of AV shuttles have been operating in the US and around the world for years.

The City of Atlanta has set the goal of being a leader in emerging transportation technologies. The Renew Atlanta infrastructure program is already equipping North Avenue as a smart city corridor, and hosted an AV demonstration along the route last year (Wickert (*12*)). MARTA is also committed to the electrification of those routes on which electric buses can meet performance requirements and concurrently reduce operating costs (Randall Guensler (*13*)). Given these initiatives, Atlanta is poised as an ideal early adopter of AV transit shuttles.

2.1 AV Demonstrations

2.1.1 CityMobil2

The European Union funded CityMobil2 research project is arguably the most well-known public AV shuttle demonstration to date. The CityMobil2 demonstration lasted from 2012 to 2016 and included three-month to six-month deployments of AV shuttles in seven different European cities. The shuttles carried "more than 60,000 passengers on fully automated on-road vehicles sharing the infrastructure with other road users" (*14*). All shuttles operated on a fixed route, though not all on a fixed schedule. While most of CityMobil2's demonstration sites shared right-of-way with primarily cyclists and pedestrians, a couple operated "in a dedicated lane, on the roadway alongside other road users, including car drivers." In addition to other road users, the CityMobile2 vehicles had to navigate physical obstacles in their path, "…including badly-parked vehicles, delivery vehicles, and construction activities…" (Pessario (*15*)). According to the project coordinators, CityMobil2 demonstrated "…the technical feasibility of automated last mile transport." (*14*).

One of the primary lessons of CityMobil2 was the importance of a fleet management component for any future AV service. Fleet management refers to the capability of a remote operator to assess unusual situations and remotely direct the AV. Two demonstration cities, La Rochelle, France, and Lausanne, Switzerland, included public roads as part of their operating routes. However, La Rochelle did not include a fleet management capability while Lausanne did. When unexpected obstacles or malfunctions occurred in La Rochelle, "…had there not been a back-up operator on board to take over manually, it would have been impossible to continue operating." (*15*). By contrast, in Lausanne, "Whenever the automated shuttle encountered an obstacle, it would come to a halt and a [fleet] operator in a remote control room would assess the situation through cameras and decide if the shuttle could continue on its way." (*15*). CityMobile2 demonstrated the need for any future AV-TOD service in Atlanta to incorporate remote fleet operator capabilities.

A final key technological demonstration of CityMobil2 was the potential for both scheduled and on-demand AV service. The Lausanne demonstration consisted of a 1.5 km route that connected a metro station with main areas of the Swiss Federal Institute of Technology campus. Two shuttles ran on a fixed schedule while two more were programmed to run on-demand, with riders requesting a shuttle via a smartphone app. Over the five month demonstration, 1,000 people used the app, and 7,000 passengers rode the shuttles (*16*).

As part of the overall CityMobil2 project, researchers surveyed more than 2,000 local residents, shuttle riders, and other roadway users such as cyclists and pedestrians in demonstration cities. More than 80 percent of riders surveyed "would have liked the temporary demonstrations to remain open and more than 70 percent wanted the [service] extended all over the city." (*14*). Most of the other roadway users surveyed also held a positive view of the AV shuttles. Among residents surveyed, the most supportive role for the AVs was "…as a complement to public transport as feeders/distributors." (*14*).

2.1.2 Waymo Early Rider Pilot

Waymo, Google's self-driving vehicle spinoff company, launched an early rider pilot program in Phoenix, Arizona in April 2017. The ongoing program provides on-demand AV service to select members of the public traveling within a geofenced area of metro Phoenix. Vehicles used in the program so far have been modified Chrysler Pacifica mini-vans outfitted with Waymo's self-driving hardware and software. It's unclear exactly how many vehicles Waymo has deployed for the early rider program, but they currently have a combined fleet of 600 automated Chrysler Pacificas® operating in metro Phoenix and other testing cities (Fitzsimmons (*17*)).

After one year of early rider program operations, Waymo disclosed that more than 400 riders per day use the AV service. The riders range in age from 9 to 69 years old and they reportedly have diverse transportation needs (Waymo (*18*)). Among the most interesting publicly disclosed findings of the pilot program have been the most common trip purposes. Topping the list is "work," followed by "restaurant", "school," and "bar," respectively. Trips for shopping and to the gym also made the top 10 list (*18*). These results suggest that riders are willing to take AVs for common every day trips; home to work, home to school, and running routine errands, like grocery shopping.

Waymo has announced plans to expand its early rider program to additional cities, including Atlanta, Georgia (Johnson (*19*)). To prepare, in early 2018, the company started building detailed 3D maps of Atlanta, which are used a base for AV navigation. As the Waymo team describes it, the mapping categorizes "features on the road, such as driveways, fire hydrants, and intersections. This level of detail helps our car know exactly where it is in the world." By comparing the pre-made maps with the AVs real-time vision, the vehicle can determine its position within 10 cm of accuracy, and without relying on "GPS technology…or lane markings" (Waymo (*20*)).

In fact, "a Waymo car's self-driving mode won't even kick in unless [the car] senses it's in a mapped zone" (Levy (*21*)). Vehicles from Navya and other AV companies operate in a similar manner. Vehicle use is geofenced to pre-mapped areas where vehicles can better differentiate what are constant road fixtures from moving or temporal objects. However, even seemingly permanent road fixtures can sometimes change. Storms can damage trees or utility poles, new pedestrian signals and crossings may be added to intersections, buildings are demolished and rebuilt, and the list goes on. The 3D maps must be kept up to date for today's AVs to operate in a safe and effective manner.

Waymo relies on the AVs themselves for continuous map updates, "our cars automatically send reports back to our mapping team whenever they detect changes. The team can then quickly update the map and share information with the whole autonomous fleet." (*20*). Other AV makers rely on similar map updating systems, and any future deployment of AV shuttles would need such a system as well. However, for ongoing map updates to be effective, fleet size matters. If an AV travels a road or route infrequently, fixed features may have changed too much for the vehicle to operate safely. The larger a service area, the larger the fleet size needs to be to help ensure updated maps, otherwise supplemental 3D mapping would need to be performed at additional cost.

The pre-mapping constraints are a primary reason this study limited AV shuttles to within a 2.0-mile radius of transit stations. Limiting, or geofencing the shuttles can help improve pickup times for riders, but it is also a requirement of the current AV technology. It is assumed that a maximum 2.0-mile operating radius (approximately 12.5 square miles) for each vehicle is currently feasible to pre-map and then continuously update with regular shuttle service, but expanding the service area to the larger metro Atlanta area would not be feasible. Actual costs of 3D mapping are beyond the scope of this thesis but will be important for any future AV transit service provider to consider.

2.1.3 Navya Autonom® Shuttle Demonstrations

While multiple electric AV shuttle makers exist, the French firm Navya has seemingly emerged as a leader in the field. Called the *Autonom®*, the company's shuttle is fully electric, and can carry up to 15 passengers. The shuttle also has wireless (induction) charging capabilities, meaning a charging pad can be installed on the ground, and all the vehicle has to do is park on top of it to recharge when not in service. A full wireless recharge takes 8 hours, which is longer than via a high-voltage plug, but the technology continues to improve (*22*).

Autonom® shuttles have been operating in test cities around the world as the company refines and improves its AV technology. Some of the most prominent public demonstrations have been in Lyon, France; Sion, Switzerland; Perth, Australia; and Las Vegas, Nevada (Navya (*22*)). While vehicle operating speed is significantly limited, these demonstration projects have shuttles operating on open roads, interacting with other vehicles, intersections, cyclists, pedestrians, and other common obstacles of the urban streetscape. The shuttles are also deployed at numerous private sites, such as corporate campuses, universities, and even airports. As of late 2017, Navya claimed to have more than 50 shuttles in service around the world, and a total of 200,000 riders (*22*).

Navya has yet to demonstrate the same level of autonomous driving capability as Waymo. However, the *Autonom*® is purpose-built for first-and-last mile transit service. It has the physical capacity to carry more people than a minivan, and comes equipped with a ramp for wheelchair access, an important requirement for transit providers (*11*). For these reasons, the *Autonom*® was chosen as the test vehicle for the remainder of this thesis. The assumption was made that the vehicle's autonomous capabilities will be significantly improved for a future shuttle and transit deployment, but the basic vehicle architecture and energy use will remain relatively similar.

2.2 AVs and TODs

Transit-oriented development (TOD) is typically located within a 0.5-mile radius, or a 10-minute walk of a transit station. In a paper titled "*Data-enabled Public Preferences*

Inform Integration of Autonomous Vehicles with Transit-oriented Development in Atlanta," an interdisciplinary research team from Georgia Tech recently explored Atlanta resident's attitudes toward AVs, and the pairing of AVs with transit (Lu et al. (*23*)). The paper explored a potential scenario in which AVs operated by MARTA "would bring people from where they live to transit stations and take people from transit stations to their final destinations."

Lu, et al., posited that AVs could increase the existing TOD radius from 0.5 to 2.0 miles, significantly expanding MARTA rail's current service footprint of 25.5 square miles to 169 square miles (*23*). The number of resident's within MARTA rail's service footprint would similarly increase from 111,000, to 606,000 people (*23*). Figure 1 below shows an overlay of the proposed expanded MARTA rail service area under the team's proposed AV-TOD scenario.

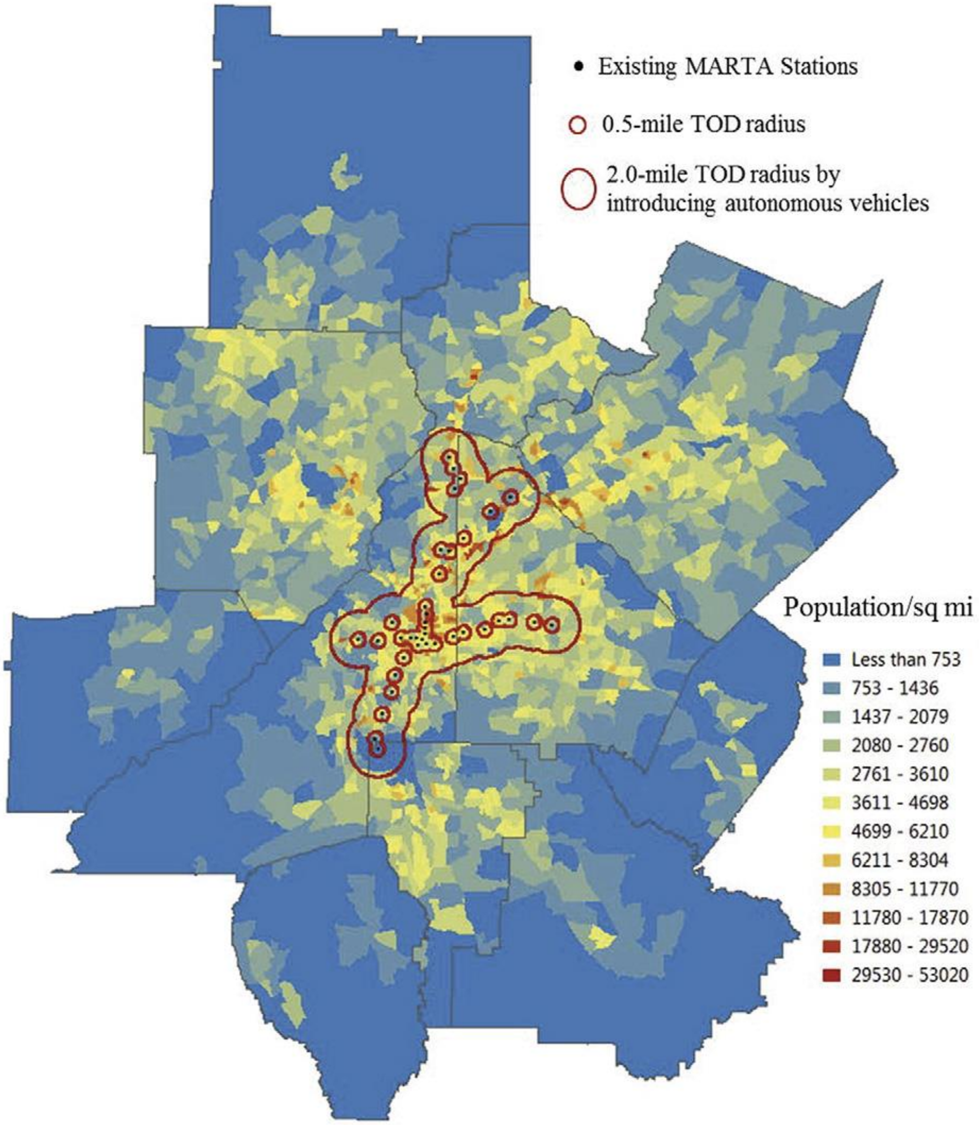

Figure 1: Potential Area and Population Served by Integrating AVs with MARTA Rail (*23*)

The research team identified additional potential benefits of pairing AVs with transit, including expanded opportunities for non-vehicle owners, and increasing higher density development opportunities. The team ultimately concluded that there is market potential to pair AVs with transit if the new service saves time or offers riders productivity benefits (*23*).

Such a system of automated shuttles certainly has the potential to greatly increase the catchment area and service population of MARTA's rail infrastructure, improve mobility for transit-captive populations, and even increase rail transit ridership (increasing the return on investment for existing rail systems). But AV systems represent a significant investment in their own right, and analyses generally proceed without much supporting data to show whether they would provide a corresponding increase in utility to riders.

This thesis aims to expand on the work of Lu, et al. (2016) and compare the simulated travel time of existing commute modes with that of the proposed AV shuttle and transit service to assess potential rider benefits (*23*).

CHAPTER 3. RESEARCH SCENARIO PARAMETERS

This thesis examines a potential future scenario in which on-demand AV shuttles serve as a first-two-mile and last-two-mile solution for MARTA's existing rail system. In the scenario, a small fleet of electric and autonomous Navya's 15-passenger shuttles are based at each MARTA rail station. The fleet size will ultimately vary by station depending on demand and the station's coverage area. For the purposes of these analyses, a shuttle is assumed to be available for every trip.

Riders within the 2.0-mile rail station service area are assumed to be able to summon a shuttle at a station (push-button or electronic means) or via a smartphone app. The AV shuttle then picks-up and delivers passengers to or from the rail station, providing riders with door-to-door convenience and climate control, but without requiring personal automobile ownership or parking.

The AV shuttles are speed limited to 25 mph, which matches the current top operating speed of Navya shuttles. Each vehicle is geofenced to serve up to a 2.0-mile radius around its designated station. Figure 2 below depicts the AV shuttle service area of each station. As station density increases, the AV shuttle service area for individual stations decrease. Stations at the end of rail lines tend to have the largest AV shuttle service area.

During higher demand periods, the shuttles will pick-up multiple passengers, much like current private ridesharing and pooling services do today. However, due to current simulation limitations, this study only examined travel times for one stop per shuttle trip. A more robust simulation model that includes multi-pickup routing will be needed to assess multiple stops per shuttle trip.

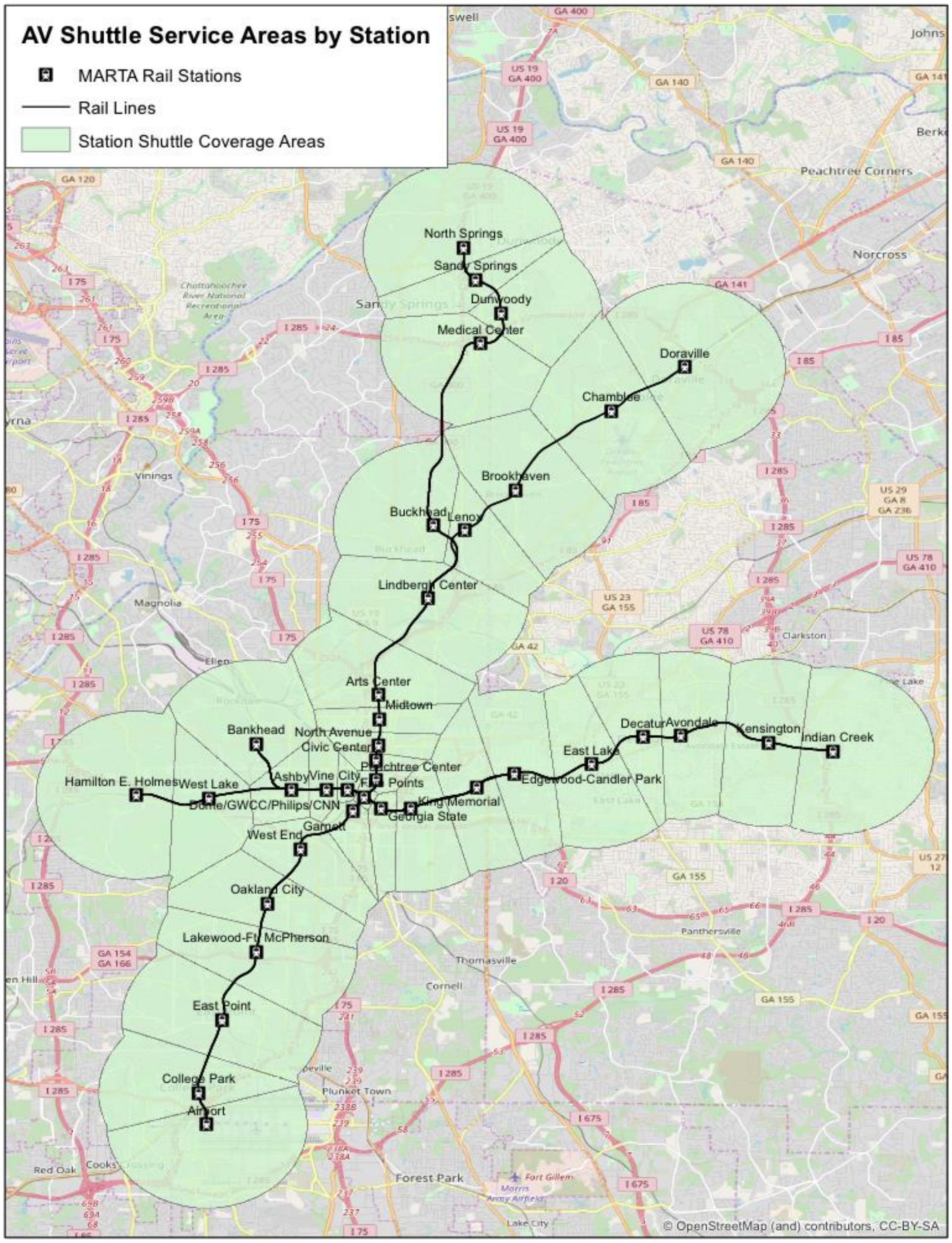

Figure 2: AV Shuttle Service Area by Station

As depicted in Figure 2, due to current simulator limitations, station coverage areas do not overlap. Meaning, if a rider is within 2 miles of multiple station they will take a shuttle to or from the closest rail station. This limitation will lead to inefficient routing, especially when the closest station is in the opposite direction of the desired destination. Or congestion is greater along the pathway between the closest station and the origin or destination.

Researchers have identified more efficient routing methods for demand responsive transit service along non-linear or heterogeneous street networks, like those found in much of metro Atlanta (Edwards (*24*)). However, those methods require a more advanced simulation model application than was used for this thesis.

Figure 3 below shows a map of MARTA's existing bus and rail network alongside the proposed AV shuttle service area. While the shuttle service is aimed at feeding riders into the rail infrastructure, the map shows that virtually every bus line intersects with at least one rail station. Given these connections, the AV shuttle service could also provide riders with more direct access to existing fixed route bus service.

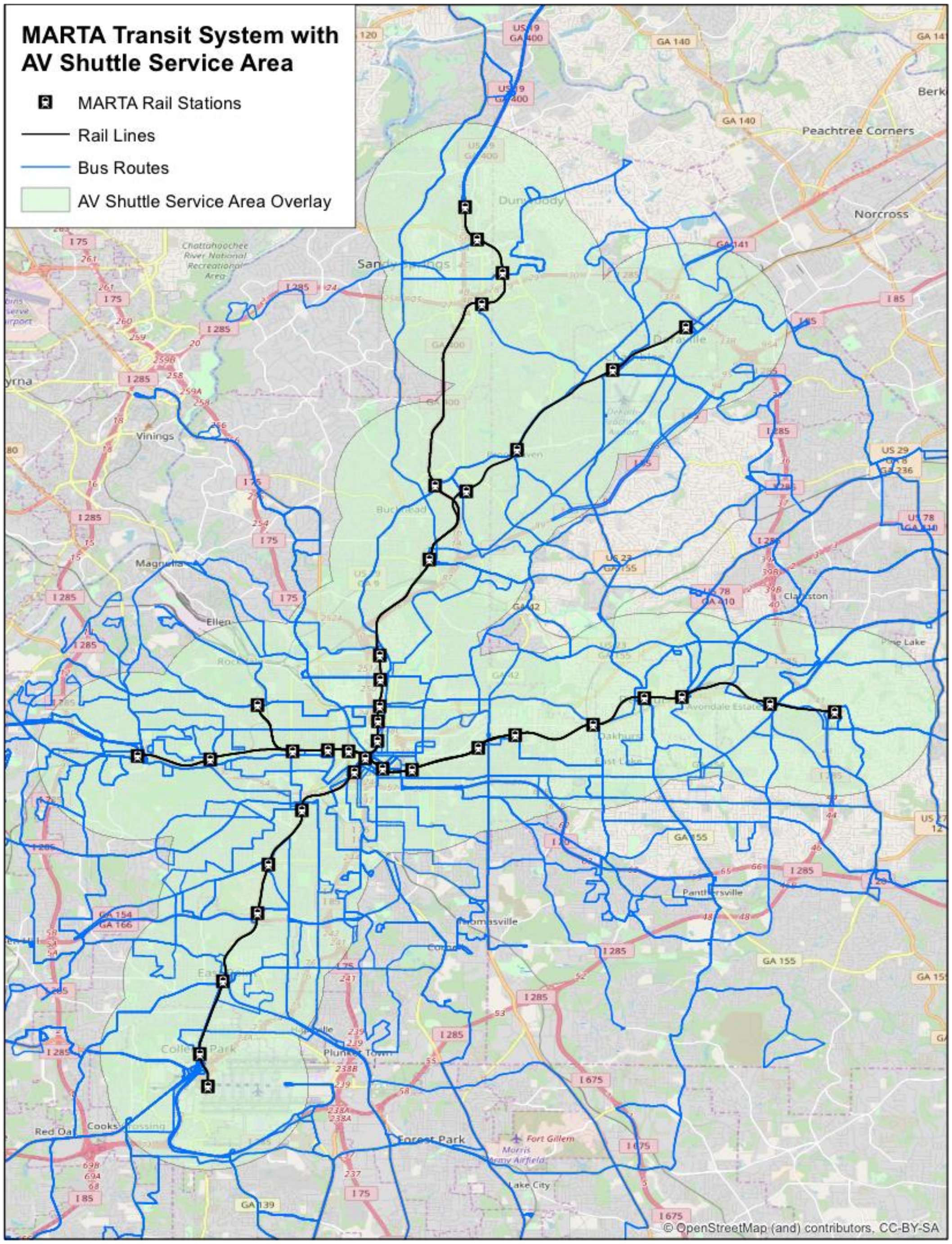

Figure 3: MARTA's Existing Transit Network with AV Shuttle Service Overlay

CHAPTER 4. DATA SOURCES AND ROUTING METHODOLOGY

The foundation of this research relies on OD pair data extracted from the Atlanta Regional Commission's (ARC) most recent Household Travel Survey, and a multimodal routing and emissions modeling platform developed by Georgia Tech researchers, referred to as the "Commute Alternatives" platform.

4.1 ARC Travel Survey and OD Pair Selection

The ARC 2011 travel diary survey was designed to collect data that could be used to better understand regional travel behavior, modify the organization's travel demand model, and improve forecasts of regional travel patterns. The survey results include travel and demographic information for more than 10,000 households within the 20-county metro Atlanta area. Travel modes captured by the survey include automobile, walk, bike, and transit for a total of 94,436 trips (Livingston (*7*)). Survey datasets include latitude and longitude information for both the origin and destination of each trip.

For this thesis, all 94,436 origins and destinations were mapped in ArcGIS® alongside a shapefile of MARTA transit rail stations (*25*). Trips with an origin and destination that both fell within a 2.0-mile radius of any MARTA rail station were selected for comparative analysis across mode alternatives. All told, 12,557 (13.3 percent) of the 94,436 travel diary survey trips began and ended within 2.0 miles of a MARTA rail station.

These trips represent those that could potentially be completed using the proposed first-and-last mile AV transit shuttle service and were used as inputs to the Commute Alternatives platform. Figure 4 below depicts the OD pair dispersion throughout the proposed AV shuttle service area.

Of these 12,557 OD pairs within the 2.0-mile, 5,721 trips were deemed to be walkable (i.e., no transit needed), and 6,802 were defined as “not walkable,” based upon an expected walking distance of more than 0.5 miles and were retained for the remainder of the analysis. This OD pair selection process is illustrated in Figure 5 below.

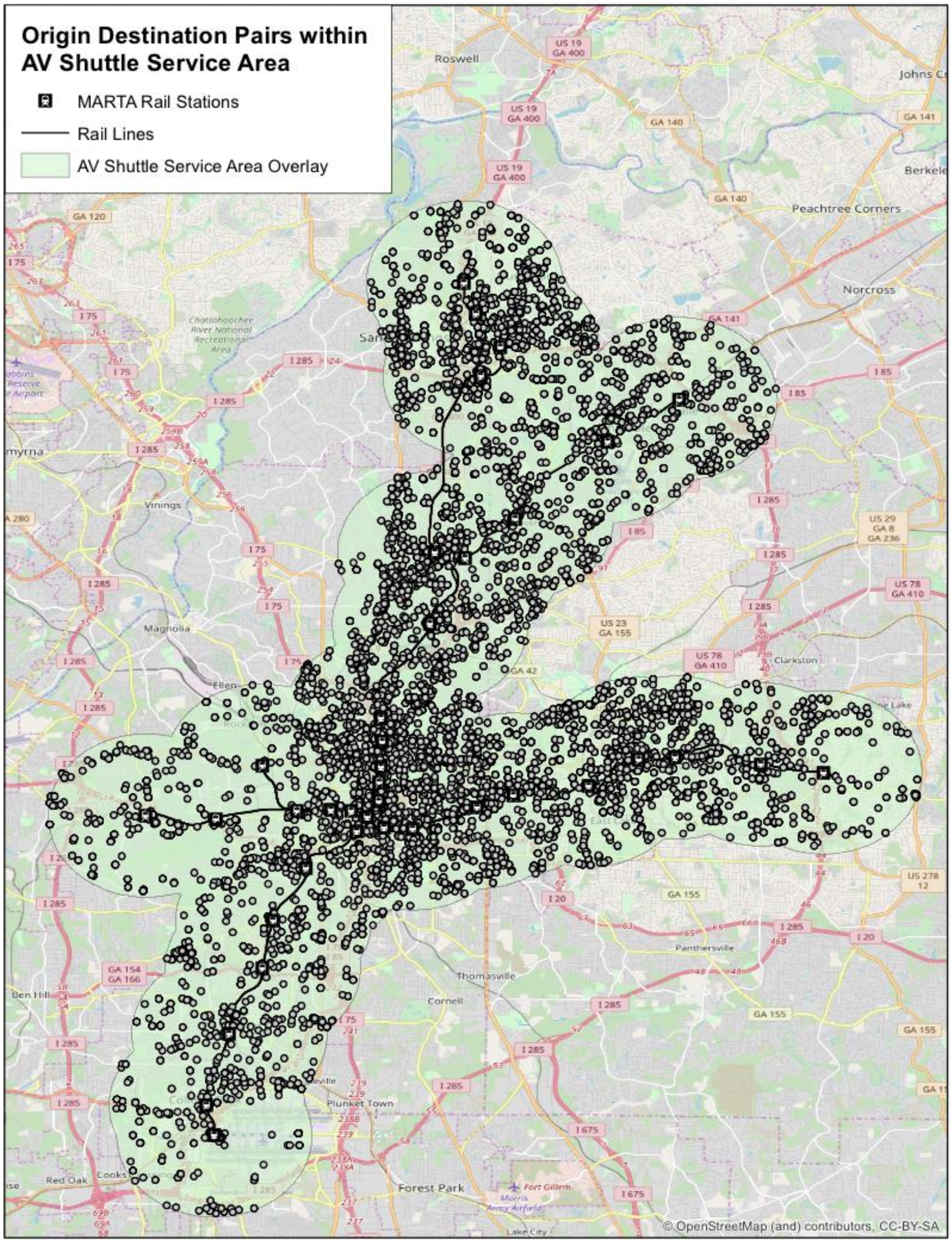

Figure 4: Origin Destination Pairs within AV Shuttle Service Area

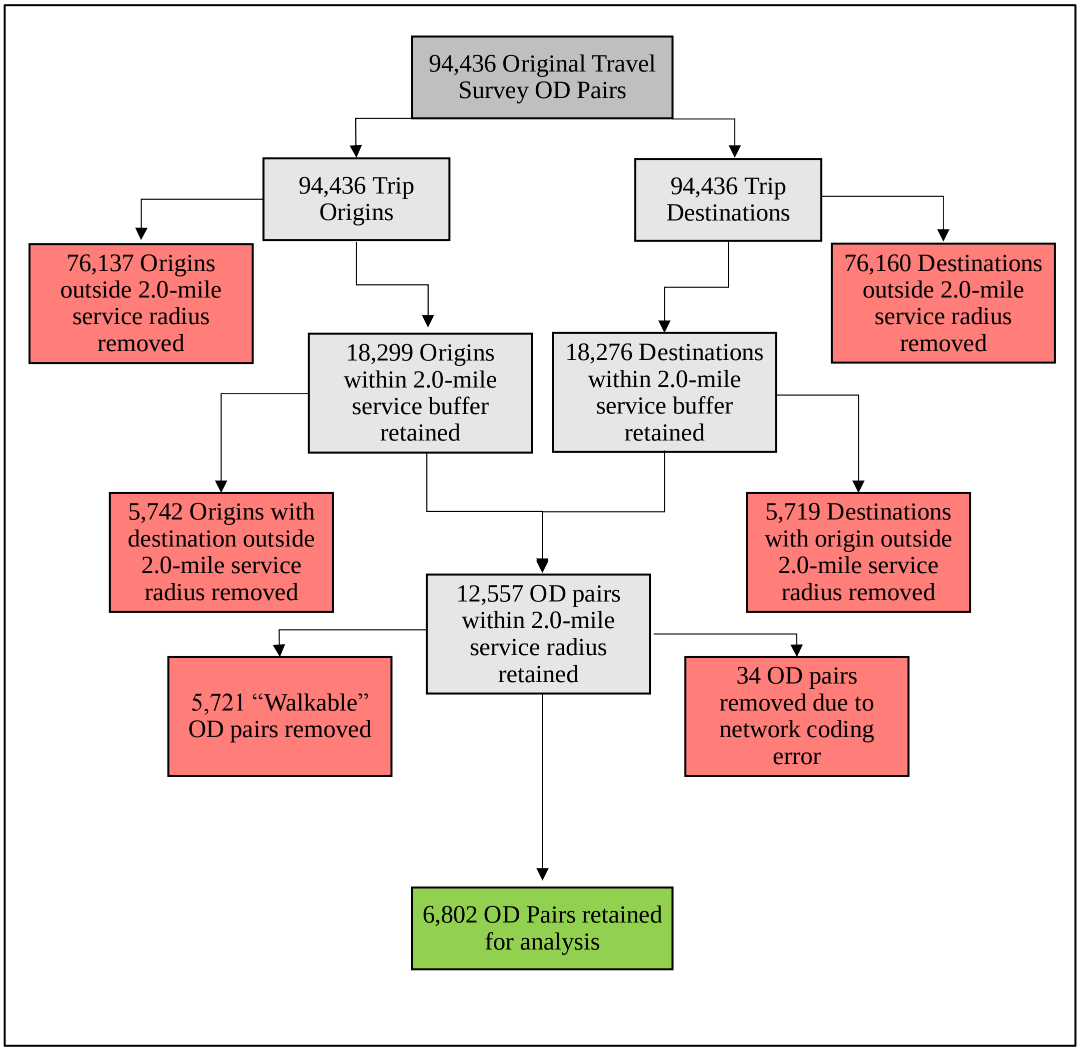

Figure 5: OD Pair Selection Flow Chart

4.2 Commute Alternatives and Existing Mode Routing

Commute Alternatives is a Python-based k-shortest path network simulation platform, composed of RoadwaySim and TransitSim modules. The system computes route, energy, and costs for multiple mode choices from any origin to any destination in the Atlanta Metro Area (*8*). Specifically, for the analyses reported in this thesis, the simulator allows users to calculate the difference in travel time, distance, and energy for a trip if traveled directly by automobile, by MARTA transit only (via walk or AV shuttle access), or by MARTA transit via park-and-ride access. The platform's k-shortest path routing modules employs the same roadway network used in ARC's Activity Based Model (ABM) for on-road travel, and a simulation of the transit network based upon General Transit Feed Specification (GTFS) data (*8*). The Commute Alternatives system passes trips across simulators, allowing analysts to track trips leaving the origin and traversing the roadway network, entering the transit network at a park-and-ride location, traversing the shortest path via combined transit routes, and then moving again through the roadway network to the trip destination.

The routing module output provides link-by-link distance and speed information throughout each trip; allowing analysts to retain this information for each collector, arterial, or highway link of a route. The route output is then coupled with an energy module that uses the speed and distance data to calculate energy consumption using rates from the MOVES-Matrix and the Argonne National Lab's GREET Model (Li et al. (*8*)*;* Xu et al. (*9*)*;* Xu et al. (*10*)*;* Guensler et al. (*26*)). This method allows for a relatively high degree of accuracy when simulating travel time and energy use. Figure 6 below shows the workflow of the Commute Alternatives platform.

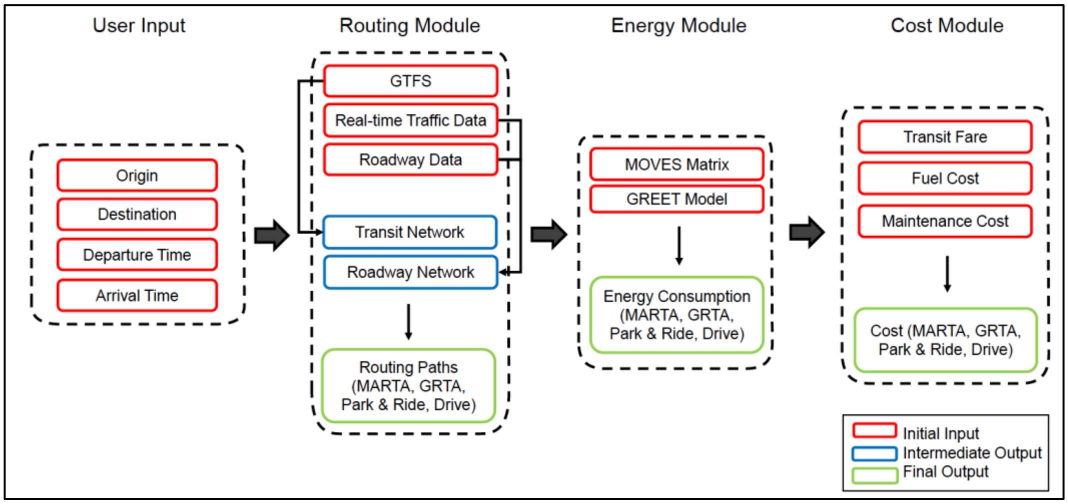

Figure 6: Workflow of the Commute Alternatives Platform (*8*)

Commute Alternatives simulation modules use k-shortest path routines to identify the shortest available path for each mode, in this case based upon minimum travel time. Each commute mode is calculated as follows (*8*):

1. Drive-only Mode: The traveler starts in a personal vehicle at the origin location, traverses the shortest path to the destination through the roadway network to the destination, and ends the trip at the destination location in their vehicle. The simulator currently ignores the time required to access the vehicle at the origin and to park the vehicle at the destination.
2. MARTA-only Mode: The traveler starts at the origin location, walks to the bus or rail transit station (selected by the simulator via shortest path analysis), traverses the shortest transit path to the destination rail station, and then walks to their destination location. The simulator allows users to transfer between current transit modes (e.g., bus-rail) where transfer time is controlled by the transit

schedule; however, this analysis is examining only those trips that both start and end within 2.0 miles of a rail transit station. Walk times use an assumed speed of 2.0 mph. Walking distance is capped at 0.5 miles from the origin or to the destination. Meaning, if a traveler must walk more than half a mile to the closest bus stop or rail station, no path is returned and it is assumed that the trip cannot be completed by MARTA alone.

3. MARTA Park-and-Ride Mode: The traveler starts at the origin location, drives to the rail transit station (selected by the simulator via shortest path analysis), traverses the shortest transit path to the destination rail station, and then walks or takes automated shuttle transit to their destination location. The simulator allows users to transfer between transit modes (e.g., bus-rail) where transfer time is controlled by the transit schedule; however, as described earlier (Figure 5) the analyses reported in this thesis currently only examine those trips that both start and end within 2.0 miles of a rail transit station. Future analyses will assess the potential benefits of adding park-and-ride trips that start outside of the 2.0-mile buffer around the origin transit station. Walk times use an assumed speed of 2.0 mph. Walking distance is capped at 0.5 miles to the destination. Meaning if a traveler must walk more than half a mile from a bus or rail station to the trip destination, no path is returned and it is assumed the trip cannot be completed by park-and-ride alone. The simulator currently ignores the time required to access the vehicle at the trip origin and to park their vehicle at the transit station (*8*).

It is also important to note that the platform only provides an output for a mode if that mode is actually reasonable for a trip (*8*). For example, a park-and-ride route will not be given for a Downtown to Midtown trip as the traveler will have to drive many miles to the closest park-and-ride lot, then take transit back into the city center. Similarly, if the destination requires more than a half-mile walk from the final transit stop, no park-and-ride output is given. The walk threshold for transit trips was also capped at 0.5 miles to or from transit stops. These platform settings help to ensure unviable commute options do not skew the resulting datasets.

4.3 Trip Segments

Drive trips traverse the roadway network from origin to destination. Trips that include transit segments all have the following three basic trip segments:

1) Origin Segment – trip origin a transit stop/station
2) Transit Segment – transit stop/station to transit stop/station
3) Destination Segment – transit stop/station to trip destination

Depending on the segment distance, travelers can access the origin segment transit station by walking, driving, or taking the automated shuttle. Travelers may access the trip destination by walking or taking the automated shuttle (a personal vehicle used earlier remains at the park-and-ride lot).

Because a half mile is considered the traditional walkable radius for a TOD, it is assumed that MARTA and AV-transit trip segments beginning or ending within 0.5 miles of a MARTA station will continue to be made on foot, and shuttle trips will only be used for trip segments between 0.5 and 2.0 miles. This assumption does not account for individuals with mobility issues, or traveler decisions made during inclement weather, but this assumption limits the scope of the study. Table 1 below shows the potential modes by trip segment for each commute option and segment distance. Trips with walking segments longer than 0.5 miles result in no path returned by the Commute Alternatives platform. Such trips are denoted in the table below by "No Route."

Table 1: Trip Segments by Alternative Commute Option and Mode

Commute Option	Mode by Trip Segment		
	Origin Segment	**Transit Segment**	**Destination Segment**
	Origin to Station < 0.5 mi		Station to Destination < 0.5 mi
MARTA-Only	Walk	Train/bus	Walk
P&R	Drive	Train/bus	Walk
AV Shuttle-Transit	Walk	Train/bus	Walk
	Origin to Station < 0.5 mi		Station to Destination > 0.5 mi
MARTA-Only	No Route - walk threshold to destination exceded		
P&R	No Route - walk threshold to destination exceded		
AV Shuttle-Transit	Walk	Train/bus	AV Shuttle
	Origin to Station > 0.5 mi		Station to Destination < 0.5 mi
MARTA-Only	No Route - walk threshold to station exceded		
P&R	Drive	Train/bus	Walk
AV Shuttle-Transit	AV Shuttle	Train/Bus	Walk
	Origin to Station > 0.5 mi		Station to Destination > 0.5 mi
MARTA-Only	No Route - walk threshold to station and destination exceded		
P&R	No Route - walk threshold to destination exceded		
AV Shuttle-Transit	AV Shuttle	Train/bus	AV Shuttle

When run, Commute Alternatives automatically calculates all available trip segments for both the MARTA and park-and-ride options. Inputting the previously identified 12,557 OD pairs into Commute Alternatives provided a control case of existing commute options to compare with the proposed AV shuttle service. The platform produced a drive path output for nearly all trips, a MARTA path for most trips, and a park-and-ride path for fewer than half of trips (related to the limiting assumption that all trips analyzed start within the 2.0-mile radius of a rail station). Table 2 below shows the total path counts for each existing modal option.

Table 2: Paths Found by Existing Modes

	Drive	MARTA-Only	Park & Ride
Paths found	11,974	7,590	5,894
Share of Service Area OD Pairs	95.4%	60.4%	46.9%

Trips without a drive path primarily represent extremely short trips, where most trips begin and end on the same network link. A few routes could not be identified (34 out of 6,802 trips, <0.5%) due to network coding errors. Of the paths found for each commute option, many were later excluded from the analysis after they were deemed "walkable." The final number of paths analyzed by each mode are shown in Table 3 of the next section.

Paths for the AV-transit option were calculated separately using a combination of the platform's drive and MARTA commute options.

4.4 AV Shuttle-Transit Routing

Before assessing the AV shuttle and transit routing paths, "walkable" trips were first removed from the dataset. For the purposes of this analysis, walkable trips were defined as trips for which the origin and destination both fall within the same MARTA rail station's service area. Many such trips were also considered "walkable" with the Commute Alternatives' MARTA-only output. However, it is also likely that some truly un-walkable trips, such as a trip going to the opposite side of the same station's shuttle service area, are inappropriately defined as walkable based solely on the OD closest station analysis, and have been excluded from the larger analysis.

The next step was to prepare OD pair datasets for each trip segment [e.g., origin, transit, destination from Table 1] to run through Commute Alternatives independently as "drive," "MARTA-only," and "drive," respectively.

The first platform run was set to "drive-only" and represented a traveler taking a shuttle from the trip origin to the closest MARTA rail station. Paths with total distances less than 0.5 miles were considered walkable as the origin is located within a station's existing TOD radius. The speed and travel time for those paths were converted to walking speeds (assuming a walk speed of 2.0 mph). Trips distances over 0.5 miles (and by default less than 2.0 miles) were considered potential AV shuttle trips.

The second platform run was set to "MARTA-only" and calculated paths from the closest rail station to the trip origin, to the rail station closest to the trip destination. This trip segment represents the transit component of the proposed new AV-transit service. While the start and end points were both rail stations, and trips were limited to those that started and ended within 2.0 miles of a rail station, many paths included an initial bus trip to access the rail station (walk to bus access).

Similar to the first run, the third Commute Alternatives run was set to "drive-only" and represented the trip segment from the closest MARTA rail station to the trip's destination, to the destination itself. Routes with a travel distance of less than 0.5 miles were converted to walking speeds. Any routes longer than 0.5 miles and less than 2.0 miles were considered potential AV shuttle segments.

Using the unique tripIDs, segments from both drive-only runs and the MARTA-only run were matched and summarized to give the full trip route, distance, and travel time.

However, the drive-only speeds and travel times had to be adjusted to match the top travel speed of 25 mph for the AV shuttles. The adjusted speeds were calculated as part of the electric energy rate simulation and will be discussed further in Chapter 7. Full AV shuttle and transit trip data were then ready to be compared with the base cases of drive-only, MARTA-only, and park-and-ride.

In total, 7,646 potential AV shuttle trips were found. However, 810 of those routes both began and ended within 0.5 miles of a MARTA station, making both shuttle segments "walkable." Those 810 trips were removed from the analysis as no shuttle component was involved and nearly all were functionally identical to the MARTA-only option (walk to transit, walk to destination). This left 6,836 trips with at least one AV Shuttle-transit path. Of those trips, 34 drive paths (<0.5 percent) could not be processed due to network coding issues, leaving 6,802 trips to compare across modes. This selection process was previously illustrated in Figure 5. Table 3 below shows the final count of paths to be analyzed by commute option.

Table 3: Path Count by Commute Option

	Drive	AV Shuttle-Transit	Marta-only	Park-and-Ride
Path Count	6802	6802	5377	4451

4.5 Example Auto and AV Shuttle Routing

For illustrative purposes, Figure 7 below shows example drive and AV shuttle-transit paths from the Commute Alternatives routing platform for a hypothetical trip. The trip represents a potential home to school trip in which the origin is a residence in Atlanta's Kirkwood neighborhood, and the destination is the Mason Building (Civil and Environmental Engineering) on Georgia Tech's campus.

Both origin and destination are approximately one mile from the closest rail station. The drive option follows a path from home to the highway, then exits on North Avenue and on Ferst Drive until reaching the destination. By contrast, the AV shuttle path follows residential streets to the closest MARTA rail station at Edgewood/Candler Park. A connection is made to another train to go from Five Points to Midtown Station, where the rider would catch a second shuttle to campus.

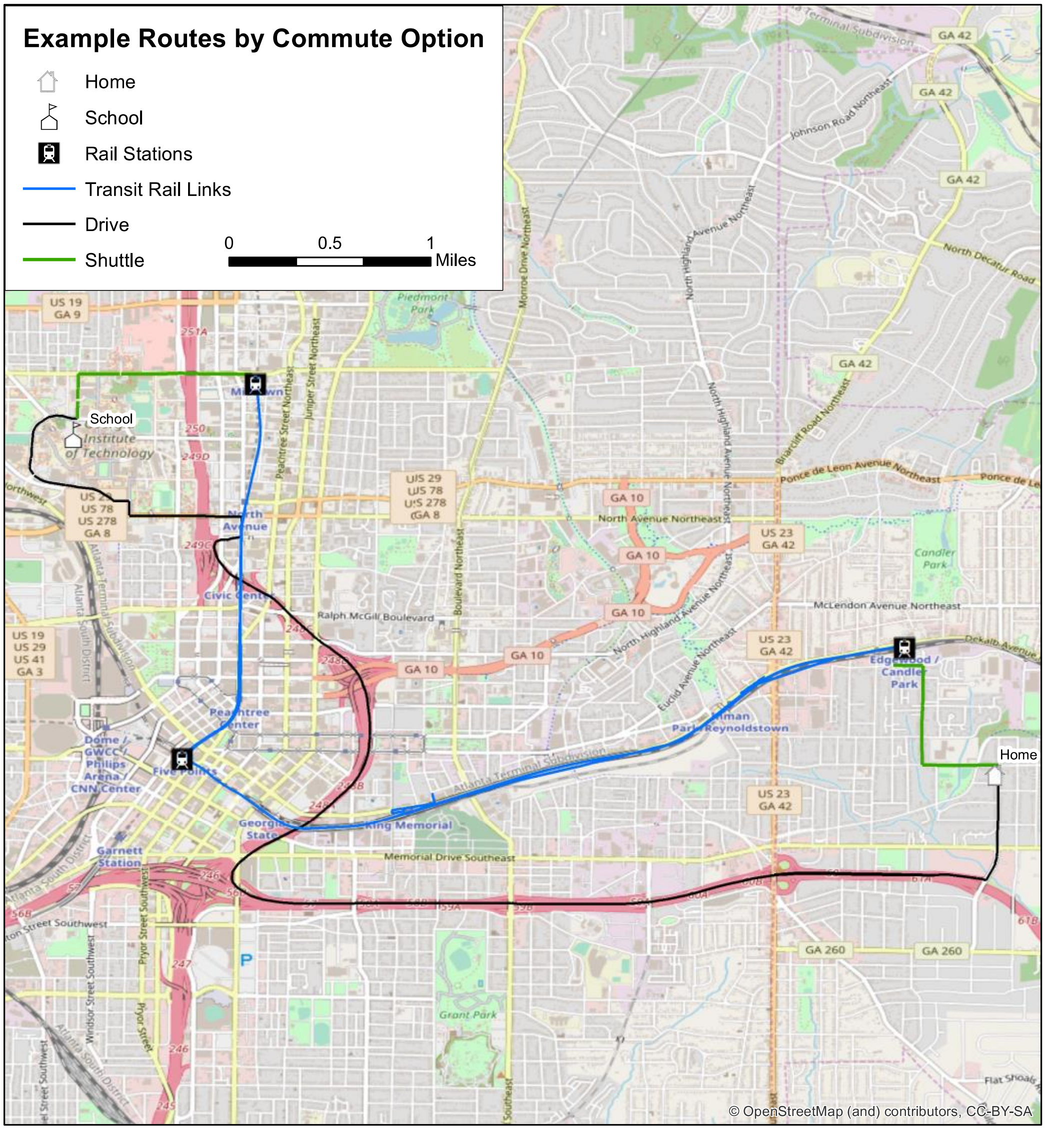

Figure 7: Example Auto and AV Shuttle-Transit Route

CHAPTER 5. TRAVEL TIME METRICS AND FINDINGS

5.1 Assessment Metrics

As its name suggests, the Transportation Research Board's *Transit Capacity and Quality of Service Manual* (TCQSM) provides transportation planners and practitioners with "…current research-based guidance on transit capacity and quality of service issues and the factors influencing both." (Parsons Brinckerhoff et al. (*27*)). Choice riders are those who choose to use transit, even though other travel options are available to them. A variety of factors often influence riders' decision to take transit, including monetary, travel time, environmental consciousness, and the ability to multi-task during a commute by reading, working, or otherwise entertaining themselves (*27*).

Among the most important factors identified for a person to decide to use transit on a regular basis is "how much longer the [transit] trip will take in comparison with the automobile" (*27*). Officially known as the Transit-Auto Travel Time Ratio, this measure is calculated by dividing the travel time of the transit trip by the travel time of the auto trip.

The travel time ratio "normalizes results, allowing segments, routes, and trips of different lengths to be compared," and it is sensitive to both "route or trip speed and directness" (*27*). For these reasons, travel time ratio was chosen as the primary measure of whether the proposed AV-transit service would provide a travel time benefit to Atlanta residents. Future analyses could examine threshold time differences (e.g., 15-minutes excess travel time) as potentially important variables. The ratio is also somewhat flexible in that it can be calculated with the entire trip time, or just in-vehicle time (eliminating transfer time). Figure 8 below is from the TCQSM and illustrates the passenger and operator perspectives with regard to different ratios (a generalization of the transit service at a range of ratios).

Transit–Auto Travel Time Ratio	Passenger Perspective	Operator Perspective
≤1	• Faster trip by transit than by auto	• Feasible when transit operates in a separate right-of-way and the roadway network is congested
>1–1.25	• Comparable in-vehicle travel times by transit and auto • For a 40-min commute, transit takes up to 10 min longer	• Feasible with express service • Feasible with limited-stop service in an exclusive lane or right-of-way
>1.25–1.5	• Tolerable for choice riders • For a 40-min commute, transit takes up to 20 min longer	
>1.5–1.75	• Round trip up to 1 h longer by transit for a 40-min one-way trip	
>1.75–2	• A trip takes up to twice as long by transit than by auto	• May be best possible result for mixed traffic operations in congested downtown areas
>2	• Tedious for all riders	• May be best possible result for small city service that emphasizes coverage over direct connections

Figure 8: Transit-Auto Travel Time Ratio Quality of Service (*27*)

For the purposes of this thesis, the auto-transit travel time ratio was calculated using the full trip time from origin to destination, including walking time, and time spent waiting for transfers. The Commute Alternatives platform currently assumes that parking is available at every origin and destination. The current version of the simulator does not directly account for time spent looking for parking, walk time from origin to parking location, or time walking from parking location to destination.

5.2 Travel Time Ratio Results

5.2.1 Drive-Only vs AV Shuttle-Transit: With and Without Parking Time

Of the 6,802 trips analyzed, only 4 percent of AV shuttle-transit routes would be faster than trips made by automobile alone, excluding parking time. Approximately one quarter of AV shuttle trips fall below the ratio of 1.5, which is considered tolerable for most choice riders. Barely 50 percent of the AV shuttle trips would fall below a ratio of 2, meaning nearly half of the simulated trips would potentially be "tedious for all riders" per the TCQSM (*27*).

Table 4 below shows the number and percentage of trips at different travel time ratios for drive and AV shuttle-transit trips. The table also how the travel time ratios change if an assumed parking time of five minutes is included. Figure 9 below depicts the dispersion of origins and destinations with auto to AV shuttle transit time ratios below 1.5.

Table 4: Drive vs AV Shuttle Travel Time Ratios

Travel Time Ratio	Parking Excluded		Parking Time Included (5 min)	
	Trip Count (6,802)	**Percentage of Trips**	**Trip Count (6,802)**	**Percentage of Trips**
< 2	3505	51.53%	5034	74.01%
< 1.5	1847	27.15%	3460	50.87%
< 1.25	895	13.16%	2270	33.37%
< 1	276	4.06%	810	11.91%

There is a significant need for more research into the amount of time spent parking per vehicle trip. In the studies Donald Shoup reviewed for his landmark paper *Cruising for Parking*, the average time drivers spent searching for a curb space ranged between "3.5

and 14 minutes" (Shoup (*28*)). Shoup went on to explain that the underlying data probably was not very accurate, and the parking time results depended on the place and time of day.

Given the lack of reliable existing literature on average time spent parking, this thesis uses the assumption that parking adds five minutes to every drive trip. This additional time accounts for one-minute walking to the parking spot at the beginning of a trip, and then an average of four minutes spent looking for a spot, parking, and walking to the destination at the end of each trip. As shown in Table 4 above, with parking time included, the auto to AV shuttle travel time ratios shift significantly. More than 50 percent of shuttle trips would fall under a ratio of 1.5, and more than 10 percent would be faster than driving.

Additional parking research is needed to capture more reliable parking data, and a more robust parking simulation is needed to capture variations in parking time per trip. In Atlanta, home-work trips typically have reliable parking but parking near a Midtown restaurant or other social venue may be difficult to find and can add significant time to a drive-only trip. As Shoup noted, parking times can vary significantly by time, place, geography and even trip purpose (*28*).

It should also be noted that there is a difference in perceived travel times between driving and transit. Travelers perceive walk, wait, and transfer times associated with transit as "more onerous" than comparable time periods spent driving in a car (*27*). Such differences in perceived travel time should be considered for future research, particularly regarding time spent searching for parking.

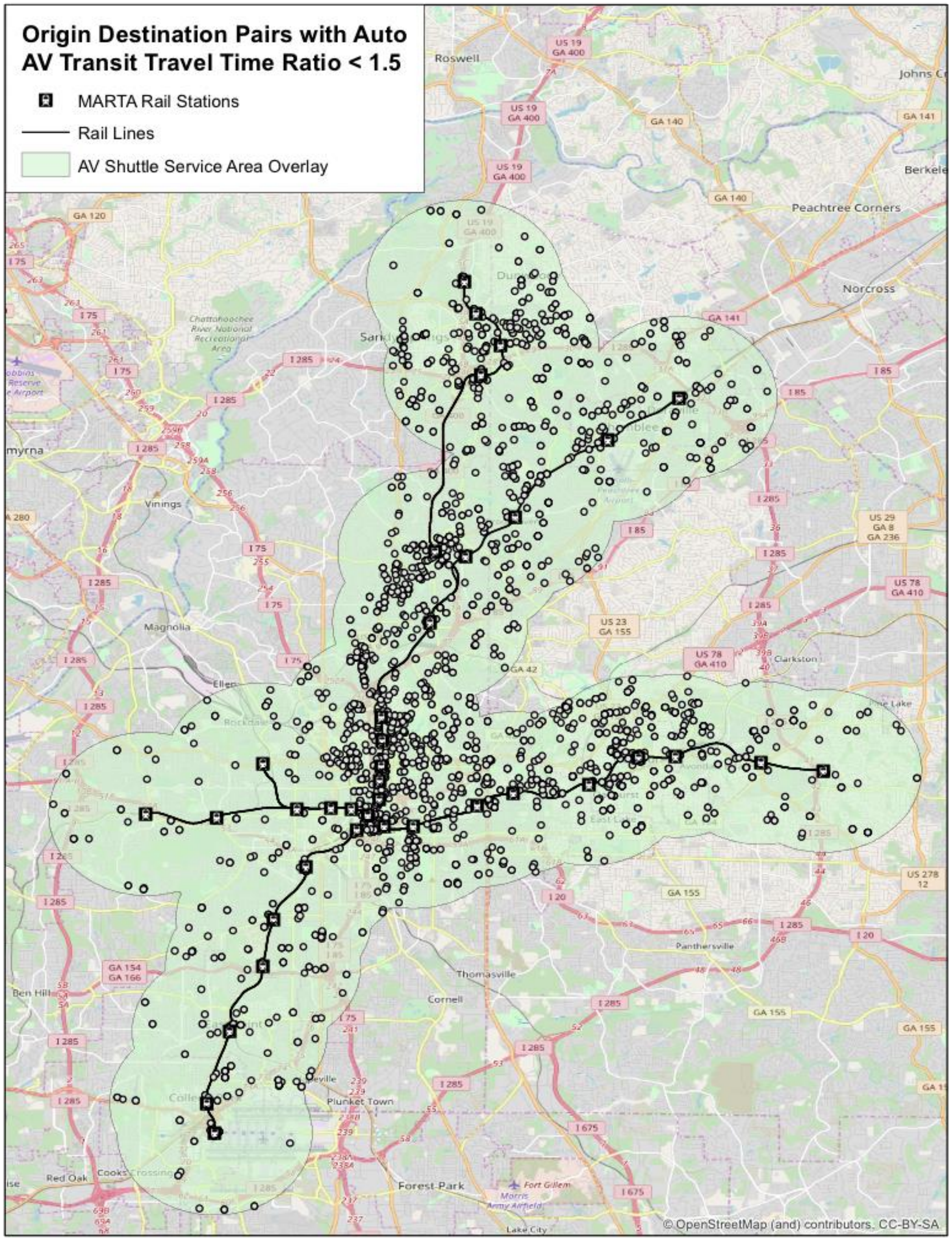

Figure 9: OD Pairs with Auto AV Shuttle Transit Ratio < 1.5

5.2.2 Assessing MARTA's Current System

With parking time excluded, the auto to AV shuttle travel time ratios may not make a compelling case for choice riders, but the ratios are far superior to those between auto and MARTA-only. As shown previously in Table 3, MARTA-only paths were not found for 1,425 of the 6,802 trips analyzed (20 percent), meaning it is not possible to take MARTA for those trips without having to walk more than 0.5 miles at either the beginning or end of the trip.

Of the 5,377 MARTA-only paths found, fewer than 20 percent of the MARTA-only trips analyzed fall below a travel time ratio of 2.0, and less than 10 percent fall below a ratio of 1.5. This means that not only would the proposed AV shuttle service significantly improve the travel time ratio of MARTA's existing system, it would also likely make transit a viable option for the 20 percent of assessed trips that are currently unserved by MARTA. Table 5 below shows the number and percentage of trips at different travel time ratios for drive-only and MARTA's current system (drive paths do not include parking time, which could significantly increase travel time in areas where parking availability is limited).

Table 5: MARTA-Only Travel Time Ratios

Travel Time Ratio	Drive vs. MARTA-only		Shuttle vs. MARTA-only	
	Trip Count (5,377)	**Percentage of Trips**	**Trip Count (5,377)**	**Percentage of Trips**
< 2	1042	19.38%	5220	97.08%
< 1.5	494	9.19%	5010	93.17%
< 1.25	305	5.67%	4790	89.08%
< 1	154	2.86%	4313	80.21%

To further illustrate the differences in travel time between the proposed new AV service and MARTA's current system, Table 5 shows the travel time ratios between the AV shuttles and MARTA-only options. More than 80 percent of potential MARTA-only trips analyzed would see a travel time improvement with the AV shuttles. Because the proposed shuttle service would only deliver riders to or from a rail station, the remaining 20 percent of trips are likely better served by a fixed route bus line, although further analysis is needed to confirm this hypothesis.

5.3 Travel Time (Minutes)

Travel time ratios alone do not tell the whole story. It is helpful to know the difference between commute options in terms of actual trip time (in minutes) and distance (in miles). After all, for a shorter trip a 1.5 ratio could mean just a couple minutes, but for a long commute the same ratio could mean the difference of half-an-hour or more.

Table 6 below shows the mean, median, and standard deviation in trip times by commute option. Driving clearly provides the shortest average trip time, as well as the lowest variability in trip time, with approximately two thirds of trips being completed in 10 to 30 minutes. Park-and-ride appears to be the next fastest and lowest variability option; however, given the 2.0-mile rail transit access assumption, park-and-ride serves the fewest number of potential trips. Results for the AV shuttle service show it would likely be a significant improvement over MARTA-only, where walking access times are significant between 0.5 miles and 2.0 miles, with the average and median travel times dropping by 26 and 35 minutes, respectively. It is important to note that these are simulated trips, and many would not be taken by transit due to the long travel time. The AV shuttles could provide an option that makes transit more viable and likely to capture some fraction of the trips currently made by driving.

Table 6: Trip Times by Commute Mode

Commute Option	Mean Trip Time (Minutes)	Median Trip Time (Minutes)	Trip Time Standard Deviation (Minutes)
Drive	19.1	16.8	10.7
AV Shuttle-Transit	38.3	33.1	19.6
Marta-only	64.7	68.1	30.8
Park-and-Ride	33.9	33.1	13.8

While these travel time results may look encouraging to current MARTA users, they include a couple key limitations. The simulation does not account for multiple passenger pickups or drop-offs, nor does it account for shuttle fleet size. The travel times assume riders are taken directly to the closest station. If another rider or two must be picked up along the way, the travel time could easily increase by a few minutes per additional rider. Furthermore, if peak hour shuttle demand is higher than the fleet size can accommodate, riders could experience significant wait times before a shuttle is available to pick them up. If riders are relying on the service to get to work or school on time, that unreliability may be the difference between using transit and a personal vehicle.

5.4 Travel Distance

In terms of distance traveled per trip, the standard drive-only option unsurprisingly has the shortest average (5.0 miles) and median (3.5 miles) distance, and matches park-and-ride for the lowest standard deviation (4.8 miles). MARTA and park-and-ride compare similarly with mean travel distances of around 6.0 miles, while MARTA has a slightly higher standard deviation between trips at 7.1 miles. The AV shuttle-transit option came in with the highest average and median distance, and deviation in distance traveled. Table 7 below details the mean, median, and standard deviation in travel distances for all commute options.

Table 7: Travel Distance by Commute Mode

Commute Option	Mean Travel Distance (Miles)	Median Travel Distance (Miles)	Travel Distance Standard Deviation (Miles)
Drive	5.2	3.5	4.8
AV Shuttle-Transit	11.6	8.7	8.3
Marta-only	8.3	6.0	7.1
Park-and-Ride	8.8	7.8	4.8

Given the proposed AV shuttle-transit service model, it is reasonable that the commute option also has higher travel distance compared to other modes. Atlanta's extensive roadway network ensures a relatively efficient route to virtually anywhere in the city, and the MARTA-only option includes fixed bus routes that often fill gaps in the MARTA rail network. For certain origins and destination, those bus lines can provide a more direct route than the rail network alone allows, however, many bus routes have large headways between busses that can result in significantly longer transfer wait times for travelers.

By contrast, the proposed AV shuttle model is aimed at feeding riders into the rail system. As previously discussed, sometimes this means a more circuitous route if riders must first travel a mile or two in the opposite direction of their trip destination to reach the closest rail station, then board a train or bus traveling toward the destination.

Further, the AV shuttle simulation specifically provides service to areas both already served by MARTA, and lower density areas that are currently unserved by MARTA without more than a 0.5-mile walk. It is reasonable for the AV shuttle service to have longer travel distance and greater variability than MARTA alone because it is serving areas that are close to rail stations, as well as currently-unserved areas further from stations. The comparatively longer travel distance of the AV shuttle-transit service should therefore not necessarily be considered a negative; the longer distance may be a positive if a greater area and population are served.

CHAPTER 6. POPULATIONS SERVED

The planning process for new transit services in the United States includes a careful review of the potential populations served, and an analysis of potential rider demand. The Federal Transit Administration (FTA) actually requires that prior to implementation, transit agencies must assess whether service changes will have a "discriminatory impact based on race, color, or national origin" (FTA (*29*)). This means that prior to any potential AV shuttle deployment, MARTA would need to thoroughly assess the communities and populations impacted to ensure the shuttles would not disproportionately negative impact based on race, color, or national origin (*30*). MARTA would also assess anticipated rider demand to calculate needed shuttle fleet size, proper deployments by station, and return on capital investment.

Common measures of equity often include an examination of minority and low-income populations served, and usually include an assessment of how costs and benefits are distributed across population groups. Estimates of ridership demand are often complex. Travel demand models are typically employed to compare travel activity across modes, demographic characteristics, land use patterns, transit captive populations, etc.

Comprehensive assessments of equity and ridership demand are beyond the feasible scope of this research. A preliminary assessment of the demographic characteristics of the proposed AV shuttle service areas was conducted using Census tract data; however, the service area bisected too many Census tracts to produce accurate results. While a complete demographic and equity assessment for the AV shuttle service area was not feasible given the data constraints, a more basic analysis was conducted using the demographic data from the ARC travel demand survey data. Specifically, each trip that was simulated was paired with household demographic data from the same travel survey for the household that made that trip to compare the potential AV shuttle trips made across traveler age, race, income, employment, and vehicle ownership status. The resulting analysis is not a true equity or demand assessment, as it examines the demographics and demand characteristics of only the 6,802 trips and does not represent the complete demographic information for the service area. Nevertheless, the results serve as a starting point for a more detailed modeling assessment that can be conducted with the ARC's activity-based travel demand model. Where appropriate, comparisons are also made to the demographics of the larger travel survey.

Household income levels and race were assessed, as they are typical equity measures. Age, employment, and non-vehicle owners were also assessed because the TCQSM guidance has identified these demographic factors as reliable indicators for a person's use of transit. Specifically, controlling for other factors, age, employment status, and number of cars per household can have a significant impact on a person's likelihood to take transit.

Per the TCQSM, "Compared to persons 16-24 years old, persons in the 25-44 and 45-64 age groups are about half as likely to use transit for a given trip, and those 65 and older are one-fifth as likely to use it" (*27*). Employed individuals are 41% more likely to use transit for a given trip than unemployed individuals. Compared to households that own zero-cars, one-car homes are just 10 percent as likely to use transit, and multi-car households are 3 percent as likely to use transit (*27*).

6.1 Captive Transit Rider Impacts

A major consideration for typical transit service changes is the impact on transit captive populations. Captive riders typically do not own a car or another reliable means of transportation and are thus dependent on transit or others to get around. These riders are often "too young, too old, or otherwise unable to drive due to physical, mental, or financial disadvantages" (*27*). Although, many young adults are increasingly choosing to go car free as a lifestyle choice (Schwartz and Rosen (*31*)).

It is important for transit agencies to consider service change impacts on captive populations because they are among the more reliable transit users. According to the TCQSM, captive riders are also significantly less responsive to fare increases than choice riders. Meaning captive transit users keep riding even when the fares go up and may be disproportionately negatively impacted by the price increases given that they have fewer available transportation alternatives.

Out of all trips in the ARC Travel Survey, only about 2.6 percent were made by non-vehicle-owning persons. Of the 6,802 trips simulated for this thesis, 355 or 5.2 percent, were taken by non-vehicle owners. It's reasonable that a larger percentage of transit captive riders would be traveling along MARTA's rail system.

Of those 355 trips, 38 trips (9.3 percent) could not be made by MARTA without walking more than 0.5 miles from either the origin or destination. The AV shuttle service would enable all of those trips to be completed by transit. Travel time ratios were again used to assess whether these captive riders would benefit from the proposed AV shuttle service. Table 8 below shows the travel time ratios between driving and the proposed AV shuttle service for trips made by transit captive riders. Nearly 10 percent of trips would be faster than by automobile alone, and approximately 30 percent would fall under a ratio of 1.5, meaning they would be tolerable even for choice riders. That said, these riders do not own a car, so the more telling measure for them is whether the AV shuttle service would improve travel speeds compared to MARTA's current service.

Table 8: Auto to AV Shuttle Travel Time Ratio for Transit Captive Trips

Travel Time Ratio	Trip Count (355)	Percentage of Trips
< 2	182	51.27%
< 1.5	108	30.42%
< 1.25	61	17.18%
< 1	30	8.45%

Table 9 below shows the travel time ratios between MARTA's existing service, and the proposed AV shuttle-transit service for transit captive riders. More than 60 percent of the simulated trips within 2.0-miles of a rail showed improved travel speeds for the AV shuttle service compared to MARTA's existing bus-rail system. Only about 20 percent of trips would have a travel time ratio above 1.5, making them comparatively "tedious."

Table 9: AV Shuttle to MARTA-only Travel Time Ratio for Transit Captive Trips

Travel Time Ratio	Trip Count (355)	Percentage of Trips
< 2	308	86.76%
< 1.5	286	80.56%
< 1.25	272	76.62%
< 1	230	64.79%

As previously noted, ratios only tell part of the story. Actual differences in travel time matter too. Table 10 below shows the mean, median, and standard deviation in travel times for simulated trips made by captive riders. By all three metrics, the AV shuttle service is superior to MARTA's current system. Both average and median trip times are nearly 20 minutes faster with the AV shuttle service, and standard deviation in trip time is cut by nearly half. Based on this simulation, it appears transit captive riders would significantly benefit from the proposed AV shuttle service.

Table 10: Travel Times for Transit Captive Trips

Commute Option	Mean Trip Time (Minutes)	Median Trip Time (Minutes)	Trip Time Standard Deviation (Minutes)
AV Shuttle-Transit	29.4	25.9	15.6
Marta-only	48.9	43.8	29.6

6.2 Trip Counts by Racial Composition

As previously noted, this study only examined the 6,802 ARC Travel Survey trips that were feasible for the proposed AV shuttle-transit service. The full travel survey, however, included approximately 94,000 trips. Comparing the racial composition of the simulated trips with the original survey dataset can give an indication of whether the proposed AV shuttle service will serve a more or less racially diverse population.

Figure 10 and Figure 11 below graphically represent the racial composition of the simulated trips, and the full travel survey trips, respectively. Table 11 shows the racial composition of both datasets in tabular form.

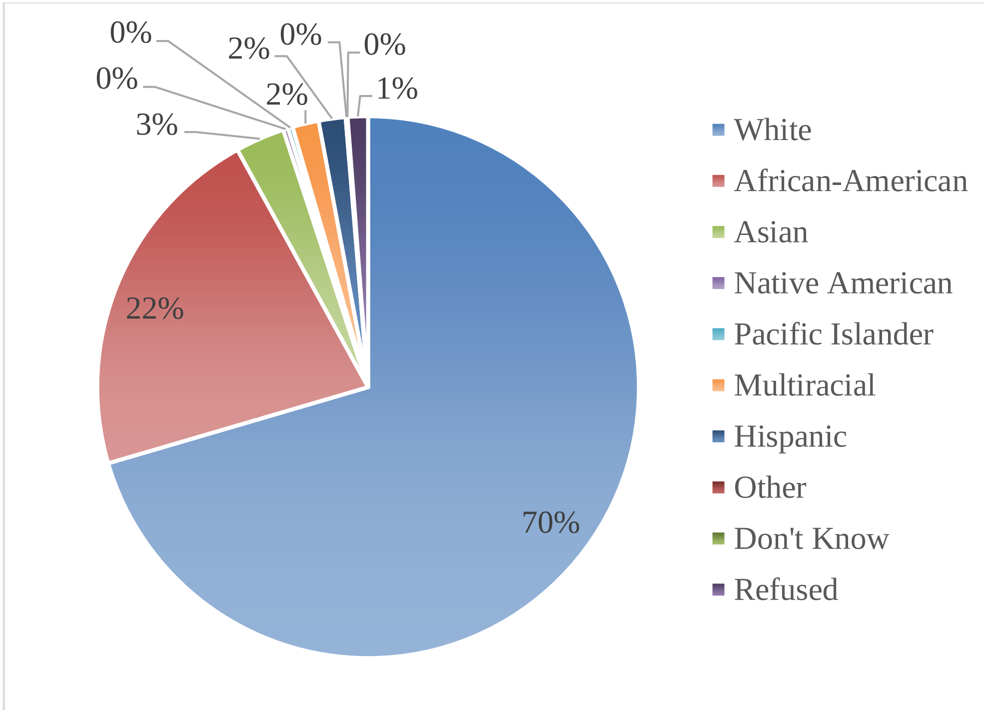

Figure 10: Racial Composition of Trips Simulated

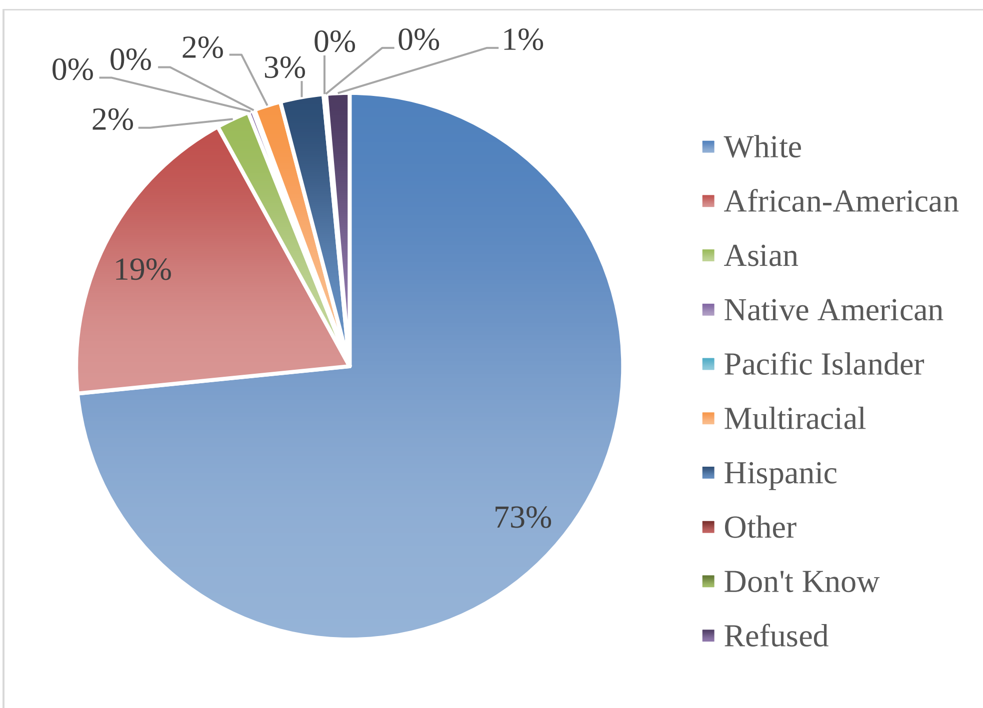

Figure 11: Racial Composition of Travel Survey

Table 11: Racial Composition of Simulated and Travel Survey Trips

Race	Simulated Trip Count (6,802)	Percentage of Simulated Trips	Travel Survey Trip Count (94,436)	Percentage of Travel Survey Trips
White	4793	70.5%	69324	73.4%
African-American	1464	21.5%	17553	18.6%
Asian	200	2.9%	1853	2.0%
Native American	20	0.3%	271	0.3%
Pacific Islander	19	0.3%	102	0.1%
Multiracial	107	1.6%	1484	1.6%
Hispanic	109	1.6%	2408	2.5%
Other	7	0.1%	115	0.1%
Don't Know	1	0.0%	32	0.0%
Refused	82	1.2%	1294	1.4%

Both datasets have relatively similar racial breakdowns. However, African-American, Asian, and Pacific Islander are marginally better represented in the simulated trips while White and Hispanic populations are slightly less represented compared to the larger travel survey. Overall, the simulated trip dataset appears to have slightly more racial diversity than the travel survey as a whole, likely due to demographic associations with residential presence within the rail station zones.

6.2.1 Travel Times by Racial Composition

Using similar methods, counts of simulated trips were summarized by auto to AV shuttle travel time ratio, and by race of the traveler. The result gives an indication of which racial groups may see the most benefit (proportionally) from the proposed AV shuttle service. The results are shown in Table 12, with a total trip count per racial category and ratio grouping, and that trip count's percentage of all trips within the ratio grouping. For example, African-Americans took 23.2 percent of all trips with a travel time ratio lower than 2.00, but they took 38 percent of all trips with a ratio below 1.00. Of the simulated shuttle trips that are faster than driving, a disproportionate share of those trips were taken by African-American travelers.

Table 12: Auto vs AV Shuttle-Transit Travel Time Ratio by Race

Travel Time Ratio	White		African-American		All Other Races	
	Trip Count (6,802)	Percentage of Trips in the Ratio	Trip Count (6,802)	Percentage of Trips in the Ratio	Trip Count (6,802)	Percentage of Trips in the Ratio
< 2.00	2405	68.6%	812	23.2%	288	8.2%
< 1.50	1258	68.1%	442	23.9%	147	8.0%
< 1.25	573	64.0%	251	28.0%	71	7.9%
< 1.00	141	51.1%	105	38.0%	30	10.9%

African-American travelers comprise just under 20 percent of the total simulated trips. However, they would realize 38 percent of the AV shuttle trips that are faster than driving alone, and 28 percent of the trips with an auto-transit travel time ratio of less than 1.25. By comparison, White travelers comprised more than 70 percent of the simulated trips, but only 51 percent of the trips in which a shuttle and transit would be faster than driving alone.

While a more detailed demographic study would be required, if the racial composition and travel patterns of the simulated trips is representative of actual metro Atlanta residents, the proposed AV shuttle service may benefit minority populations comparatively more than White populations.

6.3 Trips and Travel Time by Employment Status, Income, and Age

6.3.1 Employment Status

Of the trips simulated, 71 percent were taken by employed individuals while 29 percent were taken by unemployed individuals. Within those groupings, approximately 30 percent of the trips made by employed individuals would have an auto to AV shuttle travel time ratio less than 1.5, classifying such trips as tolerable for most choice riders. Approximately 24 percent of trips made by unemployed individuals will have an auto to AV shuttle travel time ratio below 1.5. Given these findings, of the trips analyzed, it appears employed travelers would realize slightly faster service, on average, than unemployed individuals. Employed individuals are comparatively more likely to use transit (*27*).

6.3.2 Income Brackets

Analyzing the simulation data by income bracket revealed that the trip composition was roughly equivalent to the larger ARC Travel Survey. Lower income households represented the lowest share of trips analyzed, while households earning more than $75,000 annually represented about 60 percent of bot trips simulated and trips in the larger travel survey.

A closer look at travel time ratio showed that the benefits of the AV shuttle service would be fairly evenly distributed among income groups as well. Table 13 below depicts the percentage of all simulated trips by income bracket, as well as the share of each bracket's trips that would have an auto to AV shuttle travel ratio less than 1.5, and an AV shuttle to MARTA-only travel time ratio of less than 1.0. These two ratios were used as they represent whether the shuttles could be competitive with personal automobiles, and whether they would offer an improvement over current MARTA service.

Table 13: Travel Time Ratios by Income Bracket

Income Bracket	Percentage of Trips Simulated	Share of Trips with Auto vs. AV Shuttle Travel Time Ratio <1.5	Share of Trips with AV Shuttle vs. MARTA only Travel Time Ratio < 1.0
< $30,000	14.6%	25.9%	66.7%
$30,000 to $75,000	24.5%	26.5%	65.0%
> $75,000	61.0%	28.0%	62.1%

A little more than 25 percent of trips from each income bracket would have an auto to AV shuttle ratio of less than 1.5. More than 60 percent of trips from all income brackets would have improved travel times compared to MARTA's current service.

6.3.3 Age

Of the trips simulated, approximately 16 percent were made by individuals below 25 years old, nearly 30 percent by ages 25-44, and more than half were by individuals 45 and older. For each age bracket, there was again a fairly even share of 20 to 30 percent with an auto to AV shuttle travel time ratio below 1.5. There was also a fairly even share of trips within each age bracket that would see travel time improvements over MARTA's current system. These findings are consistent with those of income and employment status in that the simulated benefits of the AV shuttle service would be well distributed across the different socioeconomic groups.

Table 14 below shows the percentage of all trips simulated by age bracket, as well as the share of each bracket's trips that would have an auto to AV shuttle travel time ratio less than 1.5, and an AV shuttle to MARTA-only travel time ratio of less than 1.

Table 14: Travel Time Ratios by Age Bracket

Age Bracket	Percentage of Trips Simulated	Share of Age Bracket's Trips with Auto vs. AV Shuttle Travel Time Ratio <1.5	Share of Age Bracket's Trips with AV Shuttle vs. MARTA only Travel Time Ratio <1
<16	10.8%	18.2%	57.6%
16-24	5.7%	23.6%	58.7%
25-44	29.2%	28.4%	65.4%
45-64	43.8%	29.4%	63.8%
>64	10.4%	25.7%	64.8%

CHAPTER 7. ENERGY COMPONENT

Similar to the route path calculations, energy consumption for the existing commute options and the electric AV shuttle option were calculated separately for each trip segment (origin to transit station, travel on transit, and transit station to destination). The Commute Alternatives platform is equipped with an energy module for each of the existing commute modes of driving, MARTA-only, and park and ride. The module calculates both upstream energy use (well-to-pump), and on road energy use (pump-to-wheels). The platform however, does not currently have the capacity to calculate energy use for on-road electric vehicles. On-road energy use for the AV shuttles was instead calculated using Autonomie, software developed by Argonne National Labs and the US Department of Energy (*32*). The shuttle's upstream energy use was calculated using the Greenhouse gases Regulatory Emissions, Energy, and Transportation (GREET) model (*33*).

7.1 Commute Alternatives Energy Module Methodology

Commute Alternatives models energy use for automobiles, transit buses, and transit rail. Using the link-by-link information derived in the routing module, the platform's energy module calculates energy use by link, accounting for the speed, distance and mode of the link, and then summarizes energy use over the entire trip (*8*).

For automobiles and buses, the platform models pump-to-wheels (PTW) energy consumption rates based on MOVES-Matrix and "models well-to-pump (WTP) energy consumption rates based on the Greenhouse gases Regulatory Emissions, Energy, and

Transportation (GREET) model" (*8*). Developed by the US Department of Energy (DOE) and Argonne National Laboratory, the GREET model allows researchers to evaluate the energy and emissions impacts of various vehicle technologies and transportation fuels, including the full fuel cycle from raw material, to processing, to distribution and use in the vehicle (*33*)).

The US Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES) is an emissions modeling system for mobile sources (*34*)). MOVES-Matrix is "a high-performance vehicle emission modeling system consisting of a multi-dimensional array of vehicle emission rates (pulled directly from the US Environmental Protection Agency's MOVES emissions model) that can be quickly queried by other models to generate an applicable emissions rate for any specified on-road fleet and operating conditions" ((*26*); Guensler et al. (*35*)).

Using the MOVES-Matrix and GREET models, the Commute Alternatives platform calculates energy use per passenger for on-road modes "by aggregating the energy use over each roadway link" (*8*). For this thesis, the vehicle occupancy levels were set to 1 for conventional automobile and 10 for MARTA bus.

For transit rail energy consumption, the platform uses Georgia Tech's Fuel and Emissions Calculator (FEC), which estimates energy use as a function of vehicle-specific power, a surrogate for engine load. The FEC model estimates energy by "applying the real world speed-acceleration profiles, generated from the second-by-second speed trace data collected by using GPS loggers on MARTA rail routes" ((*8*); Xu et al. (*36*)).

7.2 EV Shuttle Energy Methodology

Autonomie is a MATLAB based simulation software for vehicle energy consumption developed by Argonne National Laboratory and General Motors (*32*)). Unlike MOVES, Autonomie can be used to model second-by-second energy use for electric vehicles.

Autonomie has two primary user inputs for simulating energy consumption. The first is the vehicle's architecture, the second is the vehicle's drive or operating cycle. For vehicle architecture inputs, users select hardware components (i.e. chassis, wheels, motor, battery, etc.) as well as control systems, like software, regenerative braking, and battery limits. The vehicle architecture and control system determine the energy required to move the vehicle, as well as the energy supply from the battery given defined operating conditions. The vehicle's drive cycle defines the instantaneous operating conditions, including second-by-second speeds, road grade and key-on/key-off time (Slezak (*37*)).

For this thesis, Autonomie was used to estimate energy consumption of an electric and autonomous Navya shuttle under various driving conditions. The simulation results were then used to establish a simple nonlinear relationship between speed and energy, and then calculate energy consumption per trip. Before the simulation could be run however, second-by-second drive cycles were prepared.

7.2.1 Drive Cycles

For this analysis, 157 drive cycles were randomly selected from ARC data (Liu (*38*)). The resulting cycles had diverse speed profiles and represented real world driving conditions over Atlanta roadway links. Because the data set was derived from vehicle trips that included portions of vehicle operations exceeding 25 mph, the second-by-second speed data were modified to simulate the drive cycle of an AV shuttle. In each file, segments with speed data points greater than 25 mph were reduced to 25 mph. The travel time of for those cycle segments was then stretched to account for the slower travel speeds while conserving the total distance traveled.

Because roadway terrain data were not available for the drive cycles, flat terrain was assumed for all trips. The drive cycle files were converted into Autonomie ".process" files with the speed units converted from miles per hour to meters per second. The file conversions were performed using Autonomie's "import_drive_cycles" function (*32*).

7.2.2 Autonomie Simulation

With drive cycles prepared, a batch simulation run was setup with Autonomie's "run_sandbox_simulation" function with three different passenger loading levels; 1 passenger, 7 passengers, and 15 passengers (*32*). These loading levels represented the minimum, middle, and maximum loading capacity for the AV shuttle. The energy analysis of this thesis only used data from the single passenger runs; however, further analysis could be performed with the heavier passenger loads.

To model the Navya shuttle's vehicle architecture, the 100-mile midsize electric vehicle with automatic transmission setting was selected from Autonomie's default database (*32*). Other parameters were customized to fit Navya's specific architecture using technical specifications listed on the company's website (*11*). Specifically, the following parameters were selected:

- Motor maximum power = 25 Kw
- Battery size = 50 Ah
- Vehicle weight = 2470kg (1 passenger), 2960 kg (7 passenger) and 3450 kg (15 passenger)
- Vehicle frontal area = 5.59 m^2
- The initial battery state-of-charge (SOC) = 99 percent
- Vehicle stopping SOC = 10 percent

The simulation generated outputs for roughly 100 different attributes at 0.1 second resolution. A Python script extracted the relevant data for speed, energy use, and number of passengers. The extracted simulation data was then compiled by individual drive cycle and regressed to estimate energy use rates by shuttle speed.

7.2.3 On-Road Shuttle Energy Use Rates

To compare the shuttle energy use with conventional automobiles over the same roadway links, each of the simulated EV drive cycles was maintained separately and identified by the cycle's original average speed as traveled by the conventional automobile. This step ensured that the modified and simulated shuttle cycles could be matched to link routes through average speed from the original cycle. For each simulated cycle file, the average shuttle speed and average energy use rates for the average speeds were calculated in joules per mile, kilojoules per mile, and kilowatt-hours. Both the original and simulated average cycle speeds, as well as the simulated energy use rates for all 157 drive cycles can be found in Appendix A.

From the 157 EV drive cycle files, a relationship between original link speed, and the EV energy rate per mile was estimated using a simple 4th order polynomial regression (r-squared = 0.8422). The plot of the average speed relationship is shown in Figure 12 below. The derived regression formula is shown in Equation 1 with $E_{ev\ rate}$ representing the shuttle's energy use in joules per mile, and *s* representing the original average link speed in miles per hour.

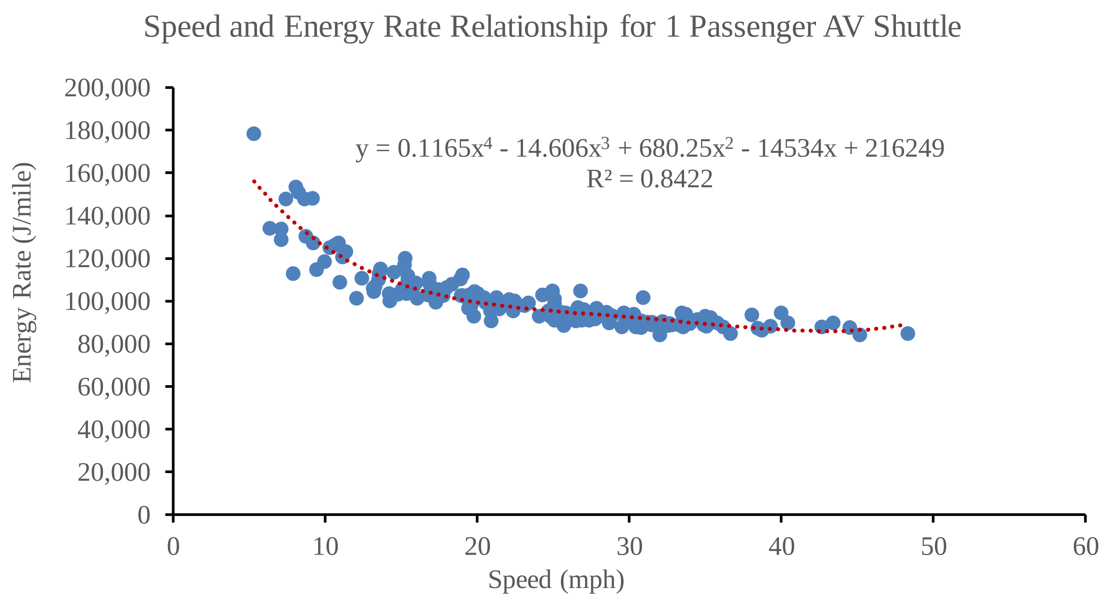

Figure 12: Average Speed and EV Energy Rate Relationship (1 Passenger)

Equation 1

$$E_{ev\ rate} = 216249 - 14534s + 680.25s^2 - 14.606s^3 + 0.1165s^4$$

Equation 1 establishes a speed-energy relationship based on distance traveled in joules per mile. An alternate, and potentially more accurate, method to model the shuttle's speed-energy relationship would be based on time, or joules per second at a given speed. To test this method, energy rates were converted to joules per second by multiplying the rate by the speed and dividing by 3,600 (the number of seconds in an hour). From there a linear regression was run between the energy rate in joules per second and speed in mph. The resulting regression equation had an R squared value of 0.98. However, further analysis between the two regression equations showed that there was not a significant difference between the two outputs. Further research should likely use the energy rate over time rather than distance; however, this thesis uses the joules per mile for simplicity.

7.2.4 Well-to-Pump Shuttle Energy Use

The AV shuttle's WTP energy use was calculated using the GREET model. As previously noted, GREET is a comprehensive modeling tool for the lifecycle impacts of transportation fuels and vehicles, "…from well to wheels and from raw material mining to vehicle disposal" (Wang (*39*)). The model is capable of evaluating more than 85 vehicle and fuel combinations, including electricity generation and distribution for EVs (*39*). Specific parameters are customizable by the user to match different geographies or energy sources.

For this thesis, the GREET model was used to evaluate energy use associated with electricity generation and distribution to MARTA for charging the EV shuttles. A multiplier needed to be established such that for every joule used on-road by a shuttle, the analysis could add the number of joules required to produce and deliver the electricity to the vehicle. To assess this upstream energy multiplier, the GREET model's default parameters were set to Well-to-Pump (WTP) analysis, and the product to be analyzed was "Electricity, Distributed US Mix" (*33*).

The GREEET pathway for the electricity generation was modified to mimic electricity generation in Georgia. Specifically, the generation mix was set to match the Energy Information Agency's (EIA) reported mix for the state, as shown in Table 15 below (EIA (*40*)).

Table 15: Georgia Utility Scale Electricity Generation Mix EIA (*40*)

Fuel Source	Percent of Georgia Electricity Generation
Natural Gas	38.8%
Coal	17.1%
Nuclear	33.5%
Renewables	10.4%

The resulting GREET upstream multiplier was 2.07 joules, meaning that for every joule of electricity used by the shuttle, 2.07 joules were used producing that electricity and transmitting it to the vehicle's charging station. To model the total energy used per shuttle mile traveled, 2.07 was multiplied by the amount of on-road energy consumed and then added to the on-road energy. For example, if 1 joule was used on a road link, 2.07 joules were used upstream, for a total of 3.07 joules of energy consumed.

7.3 Energy Results

Overall, the simulation results showed that the proposed shuttle-transit option would be more energy efficient than drive-only, MARTA's current system, and more efficient than park-and-ride for these trips that fall within the 2.0-mile buffers surrounding the rail stations. Of the three existing commute options, the greatest difference in energy use per trip was between park-and-ride and the shuttle option. The smallest difference in energy use per trip was between MARTA's current system and the proposed AV shuttle-transit service.

Table 16 below shows the percentage of trips by each mode that would be more energy efficient if completed using the proposed AV shuttle-transit option than by each existing commute option.

Table 16: Share of Trips More Energy Efficient by AV Shuttle-Transit as Compared to Existing Commute Options

	Existing Commute Options		
	Drive-Only	**MARTA-Only**	**Park-and-Ride**
Share of trips consuming more energy than AV Shuttle-Transit	88.8%	65.9%	99.7%

It is reasonable that the shuttle service would be more energy efficient per rider than existing commute options. Electric shuttles are incredibly efficient compared to conventional buses and automobiles, even when upstream electricity generation and delivery is included. Shuttle trips compared directly with MARTA likely included at least one bus segment in addition to rail, if that bus segment was instead taken by electric shuttle, the resulting emissions would be lower.

Similarly, the vast majority of drive-only trips would be more energy efficient if taken by shuttle and transit rail, even considering the further distance traveled on the shuttle routes. Electric vehicles and the electric rail systems are simply that much more energy efficient than conventional automobiles. With the exception of short drive paths matching with circuitous AV shuttle-transit path, driving will almost always be the less energy efficient mode. Finally, nearly every park-and-ride route was less energy efficient than the shuttle option due to the option's use of a conventional auto with every trip. EV shuttles would simply replace the driving portion of most every route.

Table 17 below shows the mean, median, and standard deviation in differences between the shuttle service and three existing commute options.

Table 17: Energy Use Differences Between Existing Commute Options and Shuttle-Transit Service

Comute Option Comparison	Mean Energy Difference (kWh)	Median Energy Difference (kWh)	Standard Deviation in Energy Difference (kWh)
Drive vs. Shuttle	7.17	5.03	8.37
MARTA vs. Shuttle	2.32	1.12	4.79
Park-and-Ride vs. Shuttle	43.66	34.10	32.50

Of the 6,802 drive and AV shuttle-transit trips analyzed, 6,038 or 88.7 percent resulted in more energy consumed with the drive-only mode than the shuttle option. On average, 7.2 kWh more energy was consumed per trip by driving than the shuttle option which equates to 49.8 percent more energy per trip.

For reference, 1 kWh equates to approximately 2.7 percent of a gallon of gasoline. So the average energy difference of 7.2 kWh equates to approximatly one-fifth of a gallon more gasoline per drive trip than shuttle-transit trip. The 8.4 kWh deviation in energy consumption between the modes equates to slightly less than a quarter gallon of gas for the majority of trips.

Assuming the average trip is a person's home to work commute, it will be made roughly 250 times per year. Over the course of a year, energy savings per person for home-work trips would be just shy of 54 gallons of gasoline. This represents a potentially huge source of energy and emissions reductions when extrapolated to a regional scale. A more detailed cost-benefit analysis will be needed to determine the regional energy and emissions impacts.

The per trip energy difference is slightly less between MARTA's current system and the shuttle service. As previously mentioned, the average trip difference of just over 2.0 kWhs is likely explained by the disparate energy consumption rates of buses and EV shuttles. The large difference in energy use between the park-and-ride and shuttle options, however, was surprising. A closer look at some individual routes revealed the disparity was likely due to a slightly extended drive portion of park-and-ride trips as parking lots are only available at stations outside the central city. So park-and-ride trips were routed to the nearest station with a parking lot (within reason), then traveled the additional miles by rail or bus to the destination (future analyses should exclude these trips as unreaonsable). By contrast, simulated shuttle trips took an EV directly to the closest station then rail to the destination, minimizing energy use for both segments of the trip.

Overall, the different energy use rates between the proposed AV shuttle service and existing commute options were to be expected. If implemented and used by riders, the proposed AV shuttle service could significantly curb energy consumption among Atlanta travelers.

CHAPTER 8. COST COMPONENT

Until a public transit agency actually deploys an on-road and on-demand AV system, it is unlikely the true costs of such a system will remain known. Waymo currently has the most advanced on-demand AV service in operation. As a private company that is still testing and developing the service, cost data is not publicly available.

Given the lack of publicly available data, this thesis does not provide an analysis on costs to the transit agency. Instead, it povides an overview of some estimated AV costs using existing literature, and identifies the significant knowledge gaps. A cost analysis is then provided from the perspective of the rider or commuter.

Specifically, this thesis analyzes the differences in commute costs for a traveler between the proposed AV shuttle service, driving, MARTA's existing system, and park-and-ride. The costs assessed. include transit fare, as well as per mile fuel and maintenance for the average conventional automobile.

8.1 AV Shuttle & System Costs

According to a 2016 report by the National Center for Transit Research, a Navya shuttle costs approximately $225,000. Each charging station costs just under $23,000 to install, and annual operating costs run at approximately $100,000 (*15*). Its unclear what specifically comprises the shuttle's operating costs, but a significant portion goes toward paying for an on-board human backup driver. Because the shuttle is still in its testing and development phase, a trained backup "driver" currently rides along to deploy emergency brakes or handle unexpected issues that may arise. The proposed AV shuttle-transit service would not include such an in-vehicle backup driver, but remote fleet managers would still be necessary. Remote operators would be capable of managing numerous shuttles simultaneously, decreasing the current shuttle operating costs.

Similar to the 3D map updates discussed in section 2.1.2, the remote operations would rely on strong telecommunications and information technology support. While specific telecommunications needs will vary depending on the vehicles's autonomous driving capabilties and passenger security or infotainment systems, the wireless data needs of an AV are typically much more substantial than a standard vehicles and will comprise another noteworthy operating cost.

The price of electricity will be a reliable operational cost of the AV shuttles. The Navya shuttle's current battery is capable of storing 33 kWh of electricity (*11*). In Georgia, the average price of electricity for a commercial entity is 9.5 cents per kWh (*40*). Each full charge of a shuttle will cost just over three dollars. Depending on rider demand, road grade, and need for climate control, the shuttle battery charge may be depleted and need to be re-charged multiple times per day.

Maintenance of tires, motor, and shuttle interior will also factor in to operating costs, but such costs should be lower than conventional buses given the slower operating speeds and added reliability of electric propulsion systems and optimized automated controls that reduce wear and tear on parts.

A key outstanding unknown cost, however will be that of insurance and liability. To date, autonomous vehicle technology is too new and sparsely deployed to determine the actual statistical likelihood of an accident. Preliminary data suggests that AVs may have lower rates of more severe crashes than human drivers, however, a recent analysis by the Virginia Tech Transportation Institute found that there is "currently too much uncertainty in self-driving [vehicle crash] rates to draw this conclusion with strong confidence" (Blanco et al. (*41*)).

If MARTA or another transit agency were to deploy AV service before such vehicles are demonstrably safer than human operated vehicles, the agency may need to supplement their self-insurance approach with additional liability insurance. Jurisprudence has yet to firmly establish liability precedent for AV related injuries or deaths. If and when a shuttle seriously injures someone, insurance and liability costs may increase substantially.

8.2 Trip Cost Parameters

To analyze passenger trip costs, established transit fares and vehicle operating costs were used for the three existing commute options. Trip costs for the proposed shuttle service are assessed under two fare scenarios, the first being under MARTA's existing fare structure of $2.50 per trip, with free transfers, and the second being trips that involve a shuttle cost an extra dollar ($3.50).

True costs of the drive and park-and-ride commute options include the cost of personal vehicle ownership and insurance. Such "sunk" vehicle costs were ignored for this analysis (more detailed future analysis should incorporate these costs). Parking costs may be applicable to many trips, particularly those to the Downtown area. However, since trip-by-trip parking cost data was not available, free parking was assumed for all trips. Hence, only operational costs of energy use and vehicle maintenance were examined for this thesis. Fuel costs were assessed on an energy consumption per mile basis, with the cost for a gallon of gas set at $2.30 (Li et al. (*8*)*; 42*)). An additional 5.11 cent per mile cost was assessed to capture vehicle maintenance ((*8*); *43*)). Because all existing MARTA park-and-ride lots are free, no parking cost is associated with parking at park-and-ride locations.

8.3 Trip Cost Results

8.3.1 $2.50 AV Shuttle-Transit Fare

Trip costs were compared between the shuttle service and both the drive-only and park-and-ride options. Because all park-and-ride trips involve both a MARTA fare and personal vehicle energy and maintenance, they are all more expensive than the AV shuttle service. Of the 6,802 drive-only trips analyzed, just 2,497 (36.7 percent) were more expensive than if completed by shuttle, making the proposed AV shuttle-transit service the more expensive commute option for nearly two-thirds of trips.

Table 18 below shows the mean, median and standard deviation in trip costs by commute option. At $2.73, the averge drive trip cost is slightly more than a MARTA fare, but the median drive cost is below at $1.83. This difference is due to a larger number of drive trips being of relatively short distance.

Table 18: Trip Costs by Commute Option

Commute Option	Mean Trip Cost	Median Trip Cost	Standard Deviation in Trip Cost
Drive-Only	$ 2.73	$ 1.83	$ 2.60
Park-and-Ride	$ 5.00	$ 4.27	$ 2.24

Park-and-ride trips had a much higher averge trip cost of five dollars. Given the added cost and findings from Table 6 that the shuttle service provides comparable average travel times, the proposed AV shuttle-transit service may prove to be a more desirable commuter alternative to park-and-ride. However, keep in mind again, that the trips simulated in this thesis are only those trips that fall within 2.0 miles of both an origin and destination rail station. Shuttle service at the destination end has the potental to make park-and-ride trips that start outside of the 2.0 mile origin buffer much more attractive. More research is needed in this area.

8.3.2 $3.50 AV Shuttle-Transit Fare

Raising the cost of a shuttle-transit trip to $3.50 only marginally changes the cost dynamics between driving, park-and-ride, and the AV shuttle option. With the higher fare, approximatly one quarter of drive trips and three quarters of park-and-ride trips would be more expensive than the shuttle service. Precise percentages are shown in Table 19 below.

Table 19: Share of Trips More Expensive Than AV Shuttle-Transit ($3.50 fare)

	Drive-Only	Park-and-Ride
Share of trips more expensive than by Shuttle-Transit	24.9%	77.8%

Even with the higher fare, the shuttle-transit option appears to be a competitive option with park-and-ride, given the driving cost. If full costs of vehicle ownership are taken into account, the AV shuttle option would like be even more competitive to both park-and-ride and drive-only. And, if the fair market value for parking were charged, the AV shuttle becomes even more competitive.

CHAPTER 9. CONCLUSIONS AND FURTHER RESEARCH NEEDS

9.1 Conclusions

When compared to driving-only, the proposed AV shuttle-transit service provides a benefit to only a limited number of potential riders based on travel time or cost per trip. Only 4 percent of the AV shuttle-transit trips assessed would be faster than driving, and nearly half of trips would take more than twice as long as driving. Similarly, nearly two thirds of trips would be cheaper by driving than by shuttle (albeit the parking and sunk vehicle costs are still excluded from the analysis). Factoring parking costs into the analysis may shift the cost dynamics significantly in favor of the shuttle service. From an energy use perspective, however, AV shuttle service is very appealing. Nearly 90 percent of trips assessed would see reduced energy use if completed by the shuttle-transit service instead of driving.

When compared to MARTA's existing system, the AV shuttle service provides a time saving benefit with more than 80 percent of trips assessed realizing improved travel times with the shuttles compared to walk access. Those improvements average to approximately 26 minutes saved per one-way trip. Furthermore, 20 percent of the trips assessed cannot currently be completed without riders walking more than 0.5 miles. The AV shuttle service enables all of those trips to be made by transit, significantly expanding MARTA's effective service footprint. Although the total travel distance increases, the shuttles result in lower overall energy use per passenger trip.

The AV shuttle service also appears competitive with park-and-ride in terms of travel time, energy use, and trip costs. Shuttle energy use is significantly lower than the park-and-ride option, while average travel times between commute options are within approximately five minutes of each other (again, excluding park-and-ride trips that begin outside the 2.0 mile buffer). The shuttle-transit service costs less for all trips if MARTA rates are held constant at the 2018 rate of $2.50, and remains less expensive for three quarters of trips if shuttle-transit fares are increased to $3.50.

In terms of populations served, the proposed AV shuttle service appears to provide equitable service for diverse and disadvantaged populations. Potential travel time benefits of the AV shuttles were evenly distributed across age and income brackets. While they comprise a small subset of the population, transit captive riders would see their average travel time drop by nearly 20 minutes per trip, a significant reduction for some of the most reliable transit users. This finding could be significant as MARTA seeks to curb declining ridership numbers and gain more transit users.

The simulation results were positive in terms of racial equity as well. Minority riders may even see a disproportionately larger share of the shuttle service's benefits as they comprise a greater proportion of the trips that would be faster than driving or with a travel time ratio of less than 1.5.

Despite the potential equitable service and improvements to MARTA's existing service. The results of this simulation do not make a compelling case for deploying on-demand AVs as a first-and-last mile solution. However, much more detailed study is required to assess the competitiveness of transit shuttle services to ensure that the cost of implementing the service does not significantly exceed its benefits.

9.2 Further Research Needs

The simulation for this thesis relied on ARC's ABM roadway network, meaning it's a model of Atlanta's roads, (202,000 roadway links), but not the actual full network. Many lower classification local roads and suburban neighborhood streets are missing from the ABM network, which is where the AV shuttles are expected to often operate. Running the routing platform on Atlanta's actual road network may result in the shuttles having more competitive travel times, even with the 25 mph speed cap.

An improved AV shuttle routing method would enhance the modeling work, especially in neighborhoods with overlapping station service areas. Delivering riders to the most efficient station rather than the closest could shave several minutes off of each trip. A service algorithm for heterogeneous road environments and multiple passenger pickups could also improve the model (*24*).

Further research could also explore priority signal timing for the shuttles, and impacts on the driving-only option if parking time, cost, and proximity are captured. With parking time and costs excluded, this simulation gives unintentional preference to the drive-only option. Assuming it takes five additional minutes to park significantly shifted the travel time ratios to the benefit of alternative modes, but that assumption is not research based. Additional parking research and a more robust simulation model that captures parking time per trip are needed for a more accurate comparison between modes.

Further research should also assess trips not captured within the two-mile service radius of this thesis. Specifically, potential park-and-ride commuters from well outside the two-mile buffer may benefit from taking a shuttle to their trip destination.

For energy analysis, the relationship between shuttle speed and energy consumption could be strengthened through analysis of additional drive cycles, and the inclusion of roadway incline data. As previously noted, converting the energy consumption rates from energy use per mile to energy use per second would also strengthen the analysis.

Finally, significant additional research is needed to determine the applicability of the 6,802 trips analyzed to metro Atlanta's overrall travel behavior. When developing its current travel demand model, ARC weighted trips from the travel survey differently depending in part on the demographics of the traveler. Theoretically, a similar weighting system could be applied to the trips simulated in this analysis. Until then, extrapolating the findings of this thesis should be done in a limited and considered manner. Investigating the same research problem using the regional travel demand model is also recommended.

APPENDIX A. DRIVE CYCLE AVERAGE SPEEDS AND ENERGY RATES

Drive Cycle Number	Original Average Speed (mph) for Conventional Auto	Adjusted Average Speed (mph) for EV Shuttle	EV Shuttle Energy Rate (J/mi)	EV Shuttle Energy Rate (kJ/mi)
1	5.324452	5.280356	177909.8254	177.9098
2	6.355666	5.881145	133659.1143	133.6591
3	7.116179	6.945388	133559.797	133.5598
4	7.120042	6.934732	128475.4247	128.4754
5	7.441411	7.276148	147565.2679	147.5653
6	7.916589	7.282957	112694.1342	112.6941
7	8.092043	7.749006	153019.4217	153.0194
8	8.242111	8.170496	150661.8686	150.6619
9	8.64144	8.25343	147508.4407	147.5084
10	8.743483	8.258776	129903.7289	129.9037
11	9.169311	8.941456	147927.6491	147.9276
12	9.244447	9.068108	126930.3804	126.9304
13	9.45951	8.678438	114288.9806	114.2890
14	9.973991	9.084061	118214.6904	118.2147
15	10.338118	9.709206	124784.1677	124.7842
16	10.664631	10.450928	126089.2554	126.0893
17	10.901561	9.837363	126885.3962	126.8854
18	10.975092	9.844038	108477.343	108.4773
19	11.144958	9.958291	120445.3069	120.4453
20	11.37202	10.583586	122850.0528	122.8501
21	12.082	10.366765	101053.3844	101.0534
22	12.436363	11.522201	110454.4493	110.4544
23	13.184211	11.794514	105801.8704	105.8019
24	13.234603	11.311679	104246.823	104.2468
25	13.311124	11.900205	106686.1743	106.6862
26	13.527055	11.874383	109869.9634	109.8700
27	13.574721	12.0823	112574.1914	112.5742
28	13.653485	12.850323	114662.8438	114.6628
29	14.243389	12.980499	103155.6063	103.1556
30	14.281033	12.380208	99837.61727	99.8376

31	14.535411	13.563908	113254.3215	113.2543
32	14.778654	12.706699	102758.4979	102.7585
33	15.099776	13.195495	105449.7124	105.4497
34	15.250951	13.510607	116550.1334	116.5501
35	15.27533	13.440118	119849.1444	119.8491
36	15.360611	13.244554	103083.3524	103.0834
37	15.443994	13.316387	109335.866	109.3359
38	15.448044	13.604216	111768.5882	111.7686
39	15.867801	13.204492	106717.878	106.7179
40	15.99971	13.655996	108302.1198	108.3021
41	16.081355	14.11854	100931.4548	100.9315
42	16.772495	13.913004	102670.2792	102.6703
43	16.869394	14.562222	110418.8162	110.4188
44	16.909215	14.67577	107426.2693	107.4263
45	17.287277	14.266031	99276.76684	99.2768
46	17.467314	14.674431	105013.1033	105.0131
47	17.771865	15.101678	102223.8256	102.2238
48	18.006219	15.263243	106054.2649	106.0543
49	18.366108	14.429242	107562.7548	107.5628
50	18.916827	15.608932	109963.195	109.9632
51	18.978797	15.354272	102199.5692	102.1996
52	19.030384	16.345865	112074.3234	112.0743
53	19.065524	15.155505	102322.2372	102.3222
54	19.407824	16.998849	100775.496	100.7755
55	19.445575	15.748096	96325.16563	96.3252
56	19.502604	15.804696	102551.04	102.5510
57	19.607053	17.03384	97534.86496	97.5349
58	19.655711	16.033132	99770.07168	99.7701
59	19.801657	15.984469	92563.66774	92.5637
60	19.818182	16.898465	102299.9406	102.2999
61	19.82402	16.695517	104219.1064	104.2191
62	19.851208	16.401059	100891.6103	100.8916
63	19.914455	16.400912	101876.6858	101.8767
64	19.945822	16.448374	101696.2939	101.6963
65	20.071357	16.282317	103287.0999	103.2871
66	20.186848	16.10725	100940.0264	100.9400
67	20.433755	17.172613	101288.3062	101.2883
68	20.601111	17.643545	98770.41186	98.7704
69	20.871566	15.836851	95123.39614	95.1234
70	20.947222	16.618492	90498.85761	90.4989
71	21.087012	17.309718	98205.9864	98.2060

72	21.109499	16.712655	99180.13571	99.1801
73	21.285323	17.110423	101402.7381	101.4027
74	21.466247	17.482614	95983.55146	95.9836
75	21.793623	18.091764	98483.56118	98.4836
76	22.134017	17.457579	100404.5189	100.4045
77	22.343602	17.548104	96500.77469	96.5008
78	22.378911	17.240408	96359.54485	96.3595
79	22.390851	17.526296	95230.73085	95.2307
80	22.460546	17.468341	99647.77836	99.6478
81	23.142088	17.490692	97472.0697	97.4721
82	23.406323	18.795426	98680.16261	98.6802
83	24.098362	18.083863	92532.81107	92.5328
84	24.296101	19.391192	102494.466	102.4945
85	24.552733	18.940529	93537.2391	93.5372
86	24.687004	19.433126	95138.25379	95.1383
87	24.898529	20.303286	92121.33852	92.1213
88	24.985627	19.909106	104425.2211	104.4252
89	25.078552	19.270646	100811.6486	100.8116
90	25.102804	18.55686	98501.92854	98.5019
91	25.110398	19.481186	90774.71716	90.7747
92	25.31872	19.307755	91655.84008	91.6558
93	25.489053	19.223646	93885.81182	93.8858
94	25.540905	20.080244	94604.33373	94.6043
95	25.725694	19.077887	88231.2765	88.2313
96	25.841136	19.054145	94201.88645	94.2019
97	25.938648	19.836608	90372.72464	90.3727
98	26.498165	19.291489	90512.33507	90.5123
99	26.641476	19.220414	96613.9178	96.6139
100	26.831038	20.855124	104362.6676	104.3627
101	26.900937	20.595617	90567.39539	90.5674
102	27.032157	18.655869	95701.00945	95.7010
103	27.361163	20.918899	90818.10782	90.8181
104	27.36295	19.638589	94270.67595	94.2707
105	27.636724	20.130002	91896.18916	91.8962
106	27.753697	20.059056	91261.70005	91.2617
107	27.875735	22.465448	96312.37465	96.3124
108	27.982327	21.730525	92537.52921	92.5375
109	28.202388	20.561326	93257.78112	93.2578
110	28.531373	19.485504	94554.55261	94.5546
111	28.691626	21.35081	89397.71805	89.3977
112	28.859713	21.521247	92763.33322	92.7633

113	29.55003	21.054404	87469.99961	87.4700
114	29.673234	20.795212	94259.90617	94.2599
115	29.787357	20.459193	90874.21862	90.8742
116	30.052828	21.218224	91098.74628	91.0987
117	30.336378	21.031988	93408.3486	93.4083
118	30.449131	20.68054	87532.66073	87.5327
119	30.590436	21.11634	89481.13058	89.4811
120	30.754799	21.669464	89376.57288	89.3766
121	30.805832	20.725859	87201.49312	87.2015
122	30.816365	21.869579	90333.91269	90.3339
123	30.933283	21.81208	101371.277	101.3713
124	31.196849	22.367219	89791.99137	89.7920
125	31.491259	22.843054	88618.15542	88.6182
126	31.503377	21.164973	89631.40069	89.6314
127	32.015705	22.226358	83952.7981	83.9528
128	32.202471	22.637102	90000.36956	90.0004
129	32.569061	21.944165	88180.40561	88.1804
130	32.676628	22.981627	89294.80334	89.2948
131	32.811926	21.792642	88444.51619	88.4445
132	33.299365	20.733281	88624.45585	88.6245
133	33.47314	22.914501	94188.6252	94.1886
134	33.546365	22.535097	87509.26956	87.5093
135	33.758726	22.957012	93413.57765	93.4136
136	33.988817	22.552239	89150.04938	89.1500
137	34.497832	22.167619	91150.07234	91.1501
138	34.918903	23.109739	88552.6892	88.5527
139	34.933924	22.440083	91509.58647	91.5096
140	35.003123	22.24123	92617.16045	92.6172
141	35.095933	23.169356	87803.64647	87.8036
142	35.2457	22.631442	90264.62128	90.2646
143	35.381609	22.272279	92100.46361	92.1005
144	35.783228	22.883963	89612.42013	89.6124
145	36.189224	23.009772	87445.60787	87.4456
146	36.672158	22.848792	84589.32213	84.5893
147	38.100143	22.605366	93285.17906	93.2852
148	38.464764	23.711225	86946.16167	86.9462
149	38.728316	24.588793	85977.64289	85.9776
150	39.307776	23.695788	87956.37331	87.9564
151	40.024914	23.405533	94078.48162	94.0785
152	40.449004	24.610388	89503.41729	89.5034
153	42.704838	24.403918	87709.19203	87.7092

154	43.419943	24.350235	89324.23761	89.3242
155	44.534996	24.745491	87174.54185	87.1745
156	45.165673	24.524681	83964.24809	83.9642
157	48.324755	24.862904	84578.76167	84.5788

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